JPL NO. 9950-834

DRL NO. 74/DRD NO. SE
Line Item No. 7

DOE/JPL-955089 - 81/15
Distribution Category UC-63

(NASA-CR-172983) SILICON SOLAR CELL PROCESS DEVELOPMENT, FABRICATION AND ANALYSIS (Optical Coating Lab., Inc., City of) 93 p HC A05/MF A01 CSCL 10A

N83-33315

Unclas
G3/44 13563

SILICON SOLAR CELL PROCESS

DEVELOPMENT, FABRICATION AND ANALYSIS

ANNUAL REPORT (PHASE IV)

For Period Covering
1 July 1981 to 31 December 1982

By:

P.A. Iles, and D.C. Leung

JPL Contract No. 955089

OPTICAL COATING LABORATORY, INC.
Photoelectronics Division
15251 E. Don Julian Road
City of Industry, California 91746

"The JPL Low-Cost Silicon Solar Array Project is sponsored by the U.S. Department of Energy and forms part of the Solar Photovoltaic Conversion Program to initiate a major effect toward the development of low-cost solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology by agreement between NASA and DOE."

DRL NO. 74/DRD NO. SE
Line Item No. 7

DOE/JPL-955089 - 81/12
Distribution Category UC-63

SILICON SOLAR CELL PROCESS

DEVELOPMENT, FABRICATION AND ANALYSIS

ANNUAL REPORT (PHASE IV)

For Period Covering
1 July 1981 to 31 December 1982

By:

P.A. Iles, and D.C. Leung

JPL Contract No. 955089

OPTICAL COATING LABORATORY, INC.
Photoelectronics Division
15251 E. Don Julian Road
City of Industry, California 91746

"The JPL Low-Cost Silicon Solar Array Project is sponsored by the U.S. Department of Energy and forms part of the Solar Photovoltaic Conversion Program to initiate a major effect toward the development of low-cost solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology by agreement between NASA and DOE."

ABSTRACT

In this phase, work was done in UCP, EFC materials and a comparison of UCP, HEM, and Silso materials was made. Also close to the end of this period, a new small diode approach was adapted to study properties of local areas.

For UCP Si, randomly selected wafers and wafers cut from two specific ingots were studied. For the randomly selected wafers, a moderate gettering diffusion had little effect. Moreover, an efficiency up to 14% AM1 was achieved with advanced processes. For the two specific UCP ingots, ingot #5848-13C displayed severe impurity effects as shown by lower Jsc in the middle of the ingot and low CFF in the top of the ingot. Also the middle portions of this ingot responded to a series of progressively more severe gettering diffusions. Unexplained was the fact that severely gettered samples of this ingot displayed a negative light biased effect on the minority carrier diffusion length while the non-gettered or moderately gettered ones had the more conventional positive light biased effect on diffusion length. On the other hand, Ingot C-4-21A did not have the problem of ingot 5848-13C and behaved like to the randomly selected wafers. The top half of the ingot was shown to be slightly superior to the bottom half, but moderate gettering helped to narrow the gap.

Comparison of UCP, HEM and the new Silso materials was made by simultaneous processing of typical samples of all three materials. The results of the baseline processing was similar for all three materials with HEM having a slight edge, mainly because of its single crystal portions, and Silso had a slight deficiency because it continued more fine grains. Severe gettering had no effect on HEM and only slight improvement was observed on UCP and Silso. All three materials responded to high efficiency processes, but HEM had shunting problems with BSF made by evaporated aluminum. The highest efficiencies in this test were 13.9% for UCP, 13.6% for Silso and 14.4% for HEM (with CZ control cells 15.7%).

For EFG ribbons, baseline solar cells were fabricated on fast growth ribbons. The results were lower than those of earlier slower grown ones. Also the advantage of CO_2 treated ribbon was not as pronounced as in earlier tests. Jsc and L_D results indicated variation across the width of the ribbon, but relative uniformity along the direction of growth.

Finally, a small mesa diode technique was developed and was applied to UCP materials for grain boundary study. Single crystal diodes of UCP were in general more superior to diodes containing grain boundaries, but the grain boundary was not the only factor limiting performance.

TABLE OF CONTENTS

Table of Contents Cont'd.

LIST OF FIGURES

List of Figures Cont'd.

LIST OF TABLES

List of Tables Cont'd.

I. INTRODUCTION

The objective of this program is to study and compare various unconventional silicon sheets, to understand the mechanisms that limit the efficiency of solar cells for these materials; and to correlate variations in growth parameters and performance of solar cells made from the sheets. From the start the basic approach has been to fabricate solar cells from these materials and to study their performance, rather than to measure physical properties of the sheets, and attempt to incorporate these properties into a model which predicted cell performance. Indeed, in this phase, most of the work involved the fabrication of solar cells from a number of these materials. However, as the goal of DOE has changed to more basic type of study and the number of these silicon unconventional sheet materials available for the study has been decreasing near the end of this phase, an additional approach was adapted. Small size diodes were fabricated on selected materials in order to have a more in-depth study of local area variations such as grain boundary dominated effects vs. single crystal effects on a given wafer. This approach was applied to one material (UCP) and will be applied to others in the future. In this reporting period,solar cells were fabricated and gettering tests were performed on cast UCP silicon (SEMIX) which included general material (random sources) and two specific ingots. Besides, solar cells were fabricated on the new fast growth EFG (Mobile Solar) ribbons. Then a comparison was made by solar cell fabrication and gettering tests for the three commercially available forms of cast silicon, namely UCP, Silso (Wacker) and HEM (Crystal System). Finally, the small diode study mentioned above was applied to UCP material.

II. TECHNICAL DISCUSSION

A. Solar Cells From General UCP Material (Random Sources)

1.0 Summary Of Baseline Results From Phase III

Since the following work was a continuation of work started in the last part of Phase III, a summary of those results is presented here for ease of reference. More detailed discussion and results of other back-up measurements should be referred to the Phase III Annual Report (Reference 1). Table 1 (same as Table 15 of Reference 1) summarizes the results of baseline processing of a number of UCP wafers. (The baseline process involved conservative diffusion, 91% active area, SiO AR coating). (See Reference 2.) Each of these wafers was from a different group of wafers adjacent to each other in a certain ingot (probably different ingots for different groups). The group is designated by the alphabet letter. These wafers had resistivity ~3 ohm-cm and a number of 2x2 cells were fabricated on each wafer.

Table II summarizes additional baseline results on wafers of additional groups which was not done in Phase III, but in this Phase (Phase IV). One can see that the results in general are consistent with Table 1. For both tables, UCP material had Jsc about 11% lower than Cz control and Voc was generally lower. The results of Table 1 and 2 will serve as a basis of comparison for the following tests done in this Phase (Phase IV).

2.0 Gettering Test

The gettering process used involved $POCl_3$ diffusion at 875°C for 30 minutes, followed by an etch by 2:15:5 (HF-HNO_3-CH_3COOH) to remove the junction. After the gettered layers were removed, the baseline process was used to make

2x2cm cells. Solar cell parameters (Isc, Voc, CFF, and η) were measured under AM1 at 28^{o}C test block temperature.

Table 3 summarizes the results of the gettering test. On comparing with Table 1, no increase in output can be seen as a result of the gettering. The cells made from corresponding slices (with identical alphabet D,E, etc.) were fairly close for both tests.

3.0 High Efficiency Processes

A total of four attempts were made to fabricate high efficiency cells from the UCP material. The first two attempts summarized in Table 4 were made with shallow junction (SJ), BSF by aluminum paste and MLAR coating. The third attempt summarized in Table 5 was made with SJ, BS reflector (no BSF), and MLAR, and the fourth summarized in Table 6, used SJ, BSF by evaporated Al and MLAR. (See Reference (2) for description of the processes.) For the evaporated Al BSF, a (2um) Al layer was evaporated and was alloyed for 15 minutes at 800^{o}C.

The results of Al paste by BSF as shown in Table 4 were very disappointing. There were many shunting problems as reflected in the low CFF. For those cells with reasonable CFF, there were no observable improvement of Voc as compared with baseline results (Table 1 and Table 8). Shunting problems in Al paste by BSF have been often observed in the past. It was believed to be caused by incomplete alloying of Al in the back surface and sometimes Al contamination on the front. The physical causes of such effects are not fully understood. A recent attempt by Culik and Katz of SEMIX (Reference 3) to explain it by a model of parallel junction P/N^{+} in the back surface for areas that fail to alloy,

cannot be applied in this case, for there was no N^+ in the back surface which was protected by a layer of CVD oxide during diffusion. Also notice that the shunting in the control cell in the second test was much lower than the UCP material. This suggests a material-related problem. In these two attempts the best UCP Si cell was 13.2% AM1. The expected increase of Jsc from SJ and MLAR was mainly responsible for the increase here. In order to bypass the BSF problem, two approaches were attempted. First, cells were fabricated with an evaporated BSR only. Table 5 shows that there was reduced shunting. The other approach used a 2um evaporated Al layer alloyed to form BSF. The results are summarized in Table 6. As expected, this BSF method did not have the severe shunting problems associated with Al paste BSF method. Also an increase of Voc was detected. The highest Voc of 584 mV is at least 10mV higher than any previous Voc value on UCP silicon. The highest AM1 η value was 14.1% and is the highest value for UCP silicon in these tests.

Spectral Response

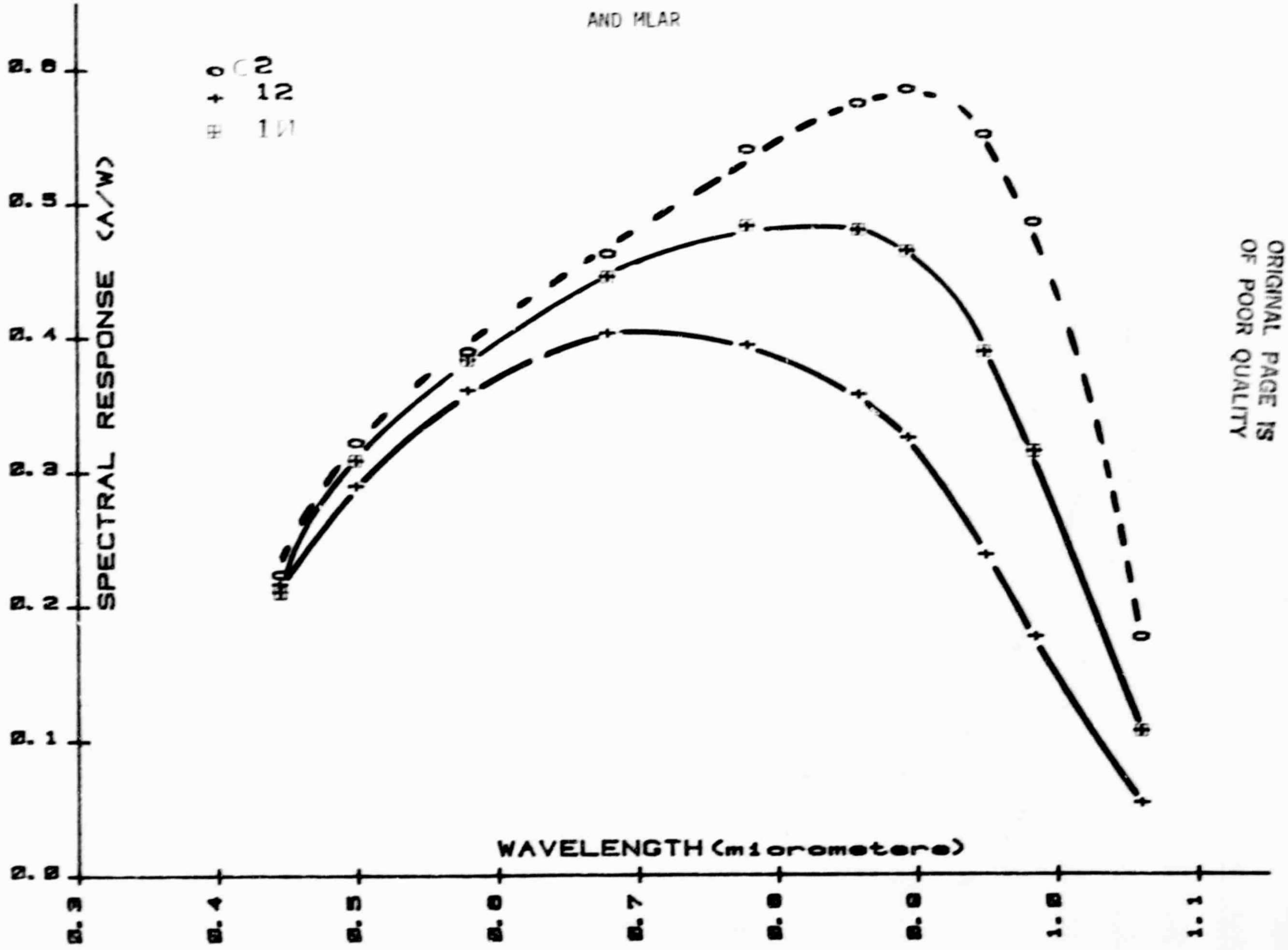
Absolute spectral response (A/W) measurements were made using a filter wheel set-up (see Reference 2 for details). Response versus wavelength of selected cells are given in Figure 1 and Figure 2. One can see that both the blue and red responses of BSR cells (Figure 1) are lower than that of the evaporated Al BSF cells (Figure 2). This is not only a BSF effect since the BSF does not affect blue response, but most likely is caused by less effective MLAR coating.

4.0 Material Study On UCP Si

It was observed that the small variation of Jsc was related to the grain size of the material. In order to understand the effects of the grain boundaries on the performance of the cells, an EBIC study was carried out on selected cells by

FIGURE 1

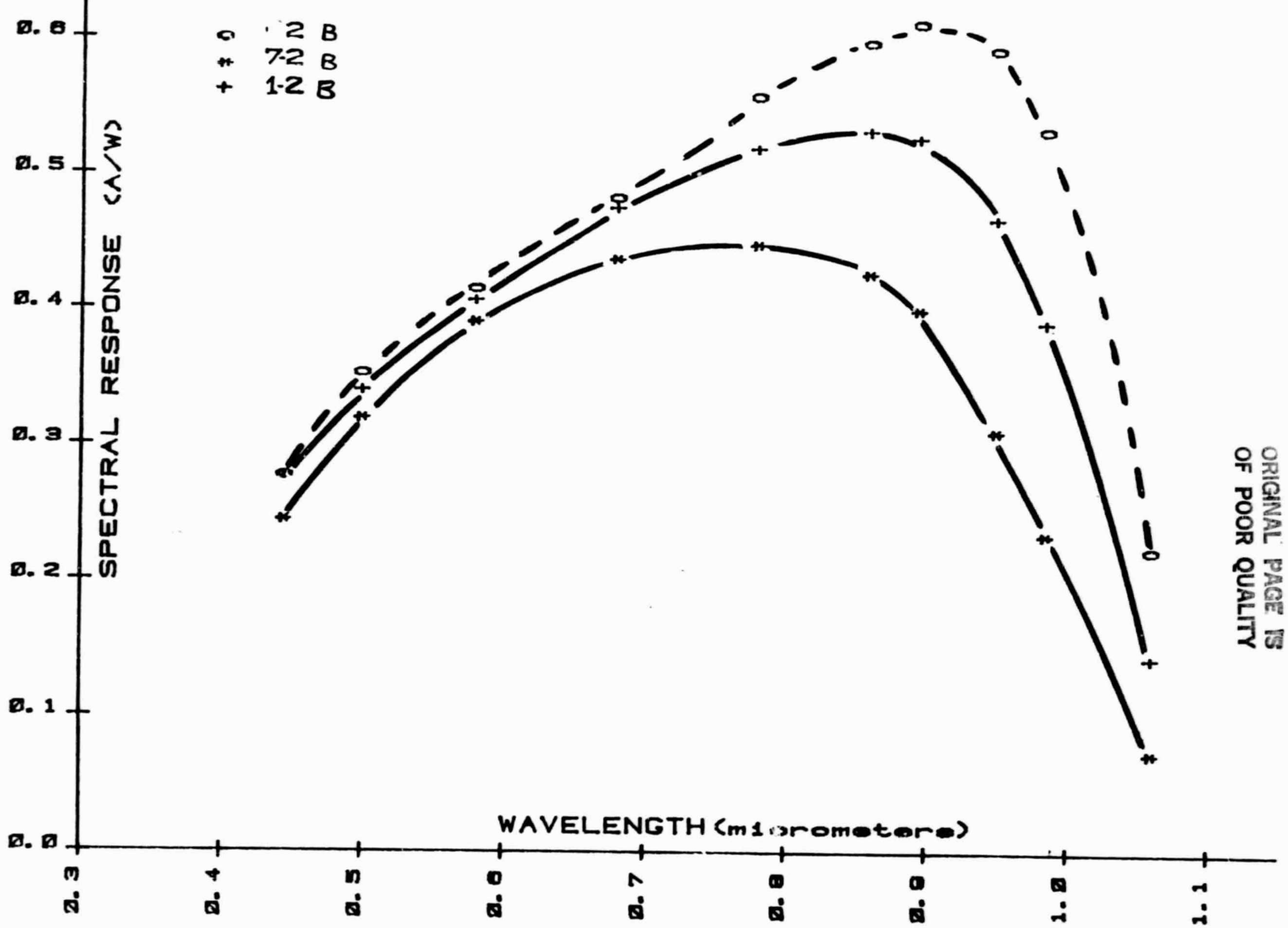
SPECTRAL RESPONSE OF SELECTED UCP SOLAR CELLS WITH SJ, BSR, (NO BSF) AND MLAR



ORIGINAL PAGE IS OF POOR QUALITY

FIGURE 2

SPECTRAL RESPONSE OF SELECTED UCP SOLAR CELLS WITH SJ, BSF BY EVAPORATED AL AND MLAR



ORIGINAL PAGE IS
OF POOR QUALITY

TABLE 1

SUMMARY OF RESULTS OF THE SOLAR CELLS FROM CAST INGOTS

BY UCP (PHASE III)

WAFER #		Voc (mV)	Jsc (mA/cm^2)	CFF (%)	η (%)	NO.OF CELLS
A-5	Ave. S.D. Range	559 6 546-570	25.1 0.9 23.0-26.4	78 1 74-79	10.9 0.5 9.9-11.8	14
B-3	Ave. S.D. Range	554 9 540-568	25.1 1.2 23.1-26.9	76 2 70-79	10.6 0.7 9.6-12.0	15
C-1	Ave. S.D. Range	550 5 542-558	25.5 0.5 24.4-26.4	76 1 73-77	10.7 0.4 9.7-11.1	12
D-3	Ave. S.D. Range	557 8 542-568	26.0 0.7 25.0-26.8	76 2 70-78	11.0 .6 9.5-11.7	12
E-7	Ave. S.D. Range	543 14 504-558	25.4 0.6 24.0-26.1	72 10 44-78	9.9 1.5 5.5-11.2	12
F-3	Ave. S.D. Range	555 7 540-570	24.9 0.8 23.1-26.1	75 2 72-78	10.4 0.5 9.4-11.5	13
Combining All Wafers	Ave. Range	553 504-570	25.3 23.0-26.9	76 44-79	10.6 5.5-12.0	78
CZ Control	Ave. S.D. Range	586 - -	28.7 0.2 28.5-28.9	78 1 77-79	13.1 0.1 13.0-13.2	3

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE 2

SUMMARY OF ADDITIONAL BASELINE UCP CELLS

CELL		Voc (mV)	Jsc (mA/cm^2)	CFF (%)	(%)
G-4 (16 Cells)	AVE.	543	24.8	75	10.0
	S.D.	7	1.1	3	.7
	RANGE	530-556	20.9-25.9	63-78	84-10.9
H-3 (15 Cells)	AVE.	546	24.9	75	10.[illegible]
	S.D.	5	.6	2	.4
	RANGE	538-552	24.0-26.0	70-77	9.6-10.8
CZ CONTROL (7 Cells)	AVE.	584	27.8	76	12.3
	S.D.	4	.2	3	.6
	RANGE	576-586	27.5-78.0	68-78	11.0-12.7

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE 3

SUMMARY OF GETTERING RESULTS

		Voc(mV)	Jsc(mA/cm^2)	CFF(%)	η (%)
D5	AVE. S.D. RANGE	557 7 546-564	25.8 .8 24.4-26.9	73 7 50-77	10.5 1.14 6.9-11.4
E5	AVE. S.D. RANGE	543.8 24.9 470-558	25.4 .7 23.6-26.4	67.7 12.7 31-76	9.4 2.0 3.6-10.8
T5	AVE. S.D. RANGE	554.6 16.9 498-570	25.0 .88 23.9-26.5	72 9 40-79	10.0 1.5 4.9-11.2
CZ CONTROL	AVE. S.D. RANGE	580 2.8 576-582	27.9 .46 27.4-28.5	75.5 2.1 73-78	12.2 .36 11.9-12.7

TABLE 4

SUMMARY OF UCP CELLS WITH SJ, BSF BY Al PASTE AND MLAR (1ST ATTEMPT)

		Voc (mV)	Jsc (mA/cm^2)	CFF (%)	(%)
D-1 (7 Cells)	AVE.	543	29.5	65	10.6
	S.D.	15	.9	11	2.3
	RANGE	514-562	28.0-30.5	45-77	6.4-13.2

(2ND ATTEMPT)

CELL		Voc (mV)	Jsc (mA/cm^2)	CFF (%)	(%)
G-2 (15 Cells)	AVE.	526	26.7	64	9.0
	S.D.	9	0.7	9	1.4
	RANGE	510-544	25.9-27.8	47-74	6.7-11.5
H-2 (14 Cells)	AVE.	537	27.2	68	10.0
	S.D.	8	1.3	6	1.1
	RANGE	530-552	23.4	56-78	7.9-11.3
CZ Control (12 Cells)	AVE.	598	32.5	73	14.2
	S.D.	9	0.5	9	2.0
	RANGE	580-610	31.6-33.1	46-79	8.6-15.9

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE 5

SUMMARY OF UCP CELLS WITH SJ, BSR

(NO BSF) AND MLAR

		Voc (mV)	Jsc (mA/cm^2)	CFF (%)	(%)
A-1 (14 Cells)	AVE.	567	27.6	77	12.0
	S.D.	5	.6	2	.5
	RANGE	554-574	26.3-28.9	73-78	11.1-12.6
CZ CONTROL (5 Cells)	AVE.	586	30.0	79	13.8
	S.D.	1	.2	1	.1
	RANGE	586-588	29.8-30.3	78-80	13.6-13.9

TABLE 6

UCP SOLAR CELLS WITH SJ, BSF

BY EVAPORATED Al, MLAR

		Voc (mV)	Jsc(mA/cm^2)	CFF (%)	(%)	BEST
UCP (12 Cells)	AVE.	572	29.5	78	13.2	
	S.D.	7	.9	1	.6	14.1%
	RANGE	560-584	23.2-31.1	77-80	12.4-14.1	
CZ CONTROL CELLS	AVE.	595	31.7	80	15.1	
	S.D.	1	.4	1	.2	15.4%
	RANGE	594-596	31.2-32.2	79-81	14.7-15.4	

JPL. Figure 3A was the result of EBIC on cell D-1-1 (by S. Hyland of JPL). Figure 3B was the actual picture of grain boundary of wafer D-7 which is from the same portion of the crystal and the enclosed region corresponds to the area in Figure 3A. One can see there exists a correspondence between the grain boundary and the dark lines of the EBIC. These indicate that many of the grain boundaries are electrically active, and would have an adverse influence on the lifetime of the material. More detailed study is needed to further our knowledge of the relationship between material properties and solar cell performance of the UCP material.

5.0 $10x10cm^2$ Cells

This is the first time such large area cells were fabricated in this program, and we can see how the $2x2cm^2$ cell data relates to the large area cells. $10x10cm^2$ UCP wafers from randomly selected from the production line were used in this study. The processing steps were similar to the conservative baseline process used in this program except a photomask was used instead of the shadow metal mask for gridlines. For this size cell, photomasks are more economical. Figure 4 shows the design of the mask which was essentially very simple and was a extension of a proven four inch circular mask to fit $10x10cm^2$ square. Table 7 summarizes the result of the cell measurements. The Voc of 533mV and Jsc of $26.9mA/cm^2$ were comparable or better than the 2x2 results of similar material. A slightly lower CFF is not totally unexpected for large area cells and the efficiency values were comparable to corresponding $2x2cm^2$ material. (A high sheet resistivity was recorded after the diffusion, therefore would expect a higher Jsc, but lower CFF). Therefore the validity of the earlier $2x2cm^2$ results in the program is confirmed.

FIGURE 3

EBIC STUDY OF UCP MATERIAL

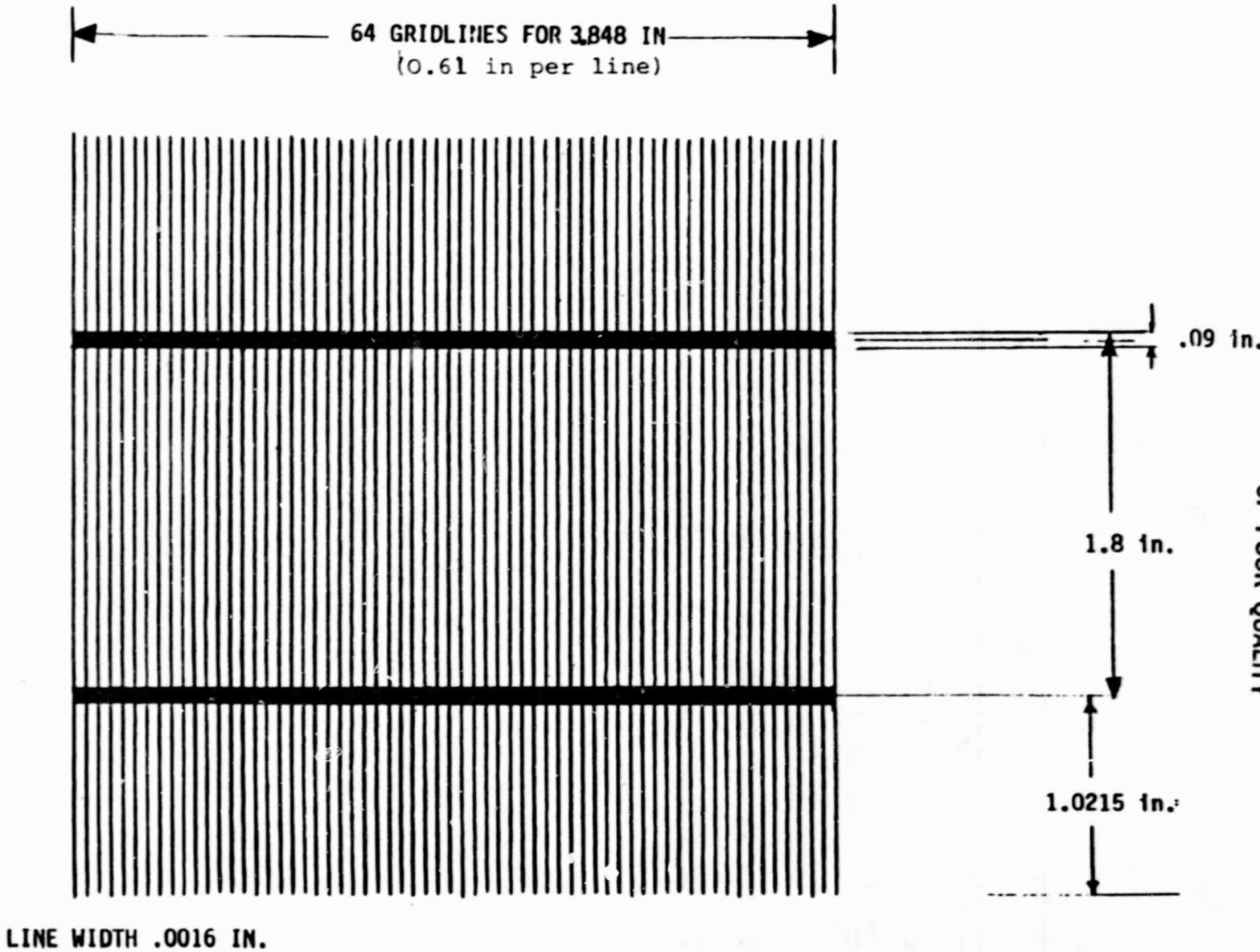
ORIGINAL PAGE IS OF POOR QUALITY

(a) EBIC PICTURE OF A 2x2 CELL ON UCP MATERIAL

(b) OPTICAL PICTURE ON THE SAME REGION OF (ENCLOSED AREA) OF A CORRESPONDING WAFER.

FIGURE 4

GRIDLINES PATTERN FOR THE 10 x 10cm^2 UCP CELL



ORIGINAL PAGE IS
OF POOR QUALITY

TABLE 7

SUMMARY OF RESULTS FOR
10 X 10 UCP CELLS FROM RANDOM SOURCES

	Voc (mV)	Jsc (mA/cm^2)	CFF (%)	(%)
AVE.	553	26.9	72	10.8
S.D.	6	.9	1	.5
RANGE	546-558	25.2-27.6	72-74	10.0-11.3

AREA = 98 cm^2

NO. OF CELLS = 6

B. Solar Cells From UCP Silicon Ingot (#5848-13C)

1.0 Parallel Baseline and Gettering Test

One quarter ingot (#5848-13C) was provided for evaluation. Figure 5 shows the dimension of this quarter ingot and the various positions from which wafers were cut. Also, Figure 5 shows where $2x2cm^2$ blanks were cut for cell fabrication in this test. From each position, i.e., top, 1/3, 2/3, and bottom, two wafers were processed. On one wafer, baseline process solar cells were fabricated. On the other wafer, a half hour gettering treatment was applied. After the gettering glass was etched-off, cells were made using the baseline process. It was observed that the grain sizes were largest on the top layer and became progressively smaller when going from top to bottom.

2.0 Solar Cell Performance and Characterization

Solar cell parameters, such as Jsc, Voc, CFF, and η were measured under AM1 at $28^{o}C$ test block temperature. Figure 6-9 show the average η, CFF, Voc, and Jsc as a function of position for both the baseline and gettered cells. The modified values for these parameters are the average of cells parameters excluding some extremely low values due to severe shunting of some of the cells, (less than 1 out of 15 cells had this problem). From Figure 6 it is obvious that the highest efficiency occurs at the bottom (despite smaller grain size), while the gettered cells generally had higher efficiency, especially on the 1/3 and 2/3 layers. From Figure 7, it can be seen that the CFF for the top layer wafers was much lower than the rest of the layers. This was from a strong recombination current component as shown in dark-current measurement (Figure 10). Also, the Voc data showed that the top layer had a smaller Voc than the rest of the ingot, and this is consistent with the recombination current dominated picture. As for the

Jsc data (Figure 9), the middle two layers i.e., 1/3 and 2/3 layers, showed lower Jsc. Figure 9 also shows that the gettering process increased the Jsc of the middle layers while there were only small improvements for the top and bottom layers. Even though the gettered Jsc values in the middle were still lower than the top or bottom, the difference had been narrowed. The above results are summarized in Table 8.

This data indicates that there were two major problems in the ingot. One kind of impurity which had segregated to the top of the ingot and precipated there caused junction recombination problems, but not lifetime problems. Microscopic observation of the top layers suggested the existence of numerous precipates. Another kind of defect (impurity) exists in the middle of the ingot and caused lifetime problems and therefore low Jsc. The latter impurity can at least be partially reduced by the gettering process. As previously mentioned, besides the above properties, occasionally there were shunting problems in the lower layers which could be due to inclusions, which were found by microscopic observation even in the lower layers. However, these shunting problems were not dominant.

Spectral Response

Absolute spectral response (A/W) was measured using the filter wheel set-up. Plots of response of selected cells are presented from Figure 11 to Figure 14 with comparisons of corresponding baseline and gettered cells. A general improvement of the gettered cells was observed.

Minority Carrier Diffusion Length

Effective minority carrier diffusion length (L_D) was obtained using the short circuit current method (see Reference 2 for details) of the finished solar cells.

Results from selected samples are summarized in Table 9. It shows that a large improvement of L_D occur after gettering in all layers even though the Jsc data did not improve proportionally. Nevertheless, the gettering process had a marked effect on the bulk lifetime at least in the dark.

Light Spot Scanning

Localized photoresponse of the UCP solar cells was obtained by small light spot scanning. (See Reference 2 for details.) Typical scanning results are given in Figure 15 and Figure 16. Figure 15 shows a scan from a top layer cell where a high density of precipitates existed and Figure 16 shows a scan from a middle layer cell.

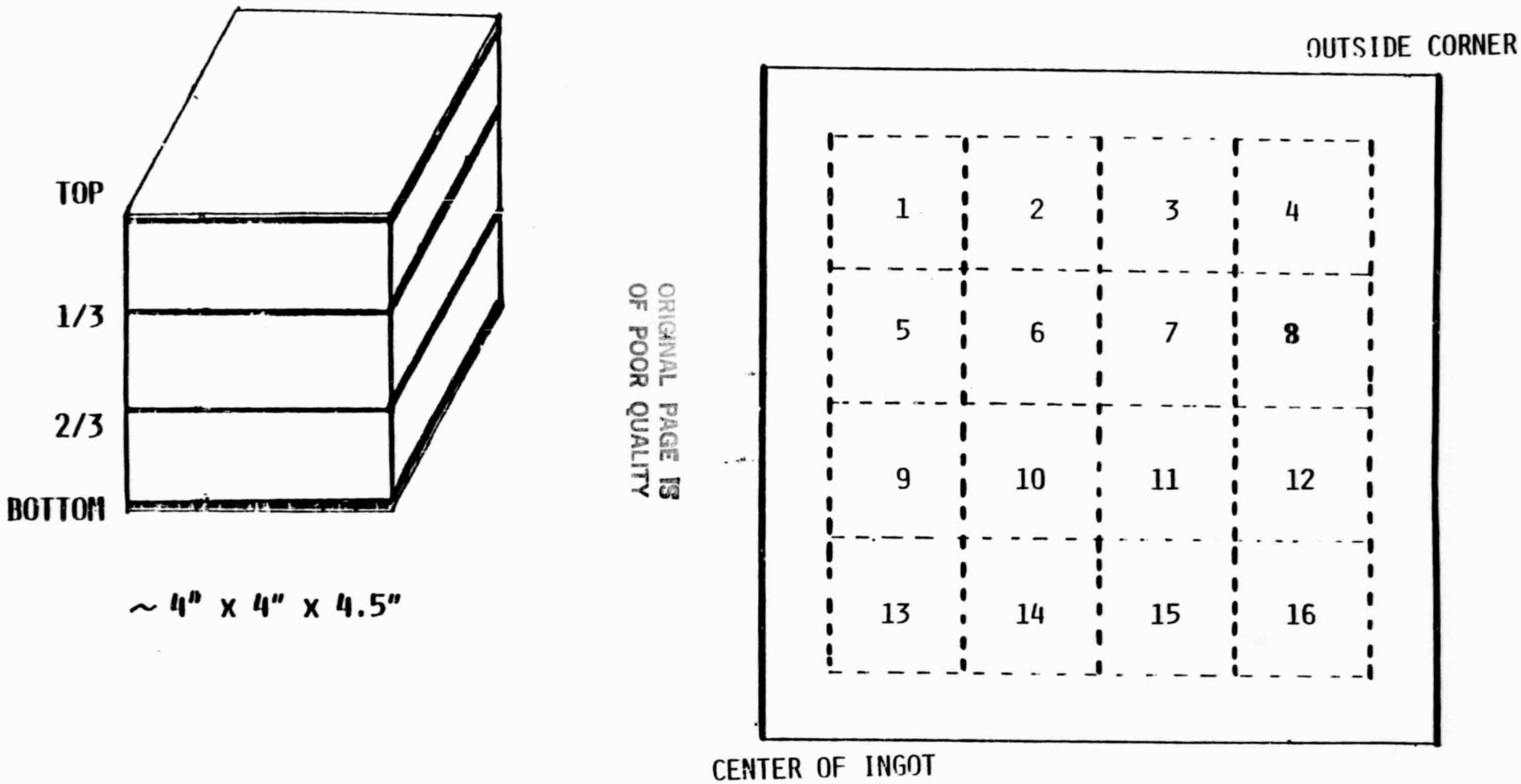
One can see that the basic current level of the top cell is substantially higher than the middle one, even though the precipates caused local deterioration of Jsc. This is also consistent with the interpretation of low bulk lifetime in the middle layers.

3.0 High Efficiency Process

For the high efficiency processing, wafers were selected from the bottom of the ingot because that was where the best baseline process performance was observed. On one of the wafers, shallow junction, multi-layer AR and Al paste BSF processes were used. On another wafer, the same processes were used except that evaporated Al BSF was used instead of Al paste BSF. These two steps were used because of previous shunting problems using Al Paste BSF on UCP material (see Section A). Table 10 summarizes the results for the two wafers. The Al paste BSF still caused some shunting trouble. In this test only portions of the wafer which were not in contact with the alloying boat surface

FIGURE 5

UCP INGOT # 5848-13C



THE CELL'S # AND THEIR RELATIONS TO THE ORIENTATION OF THE QUARTER INGOT ARE MARKED

FIGURE 6

AVERAGE EFFICIENCY OF DIFFERENT LAYERS OF INGOT 5840-13C

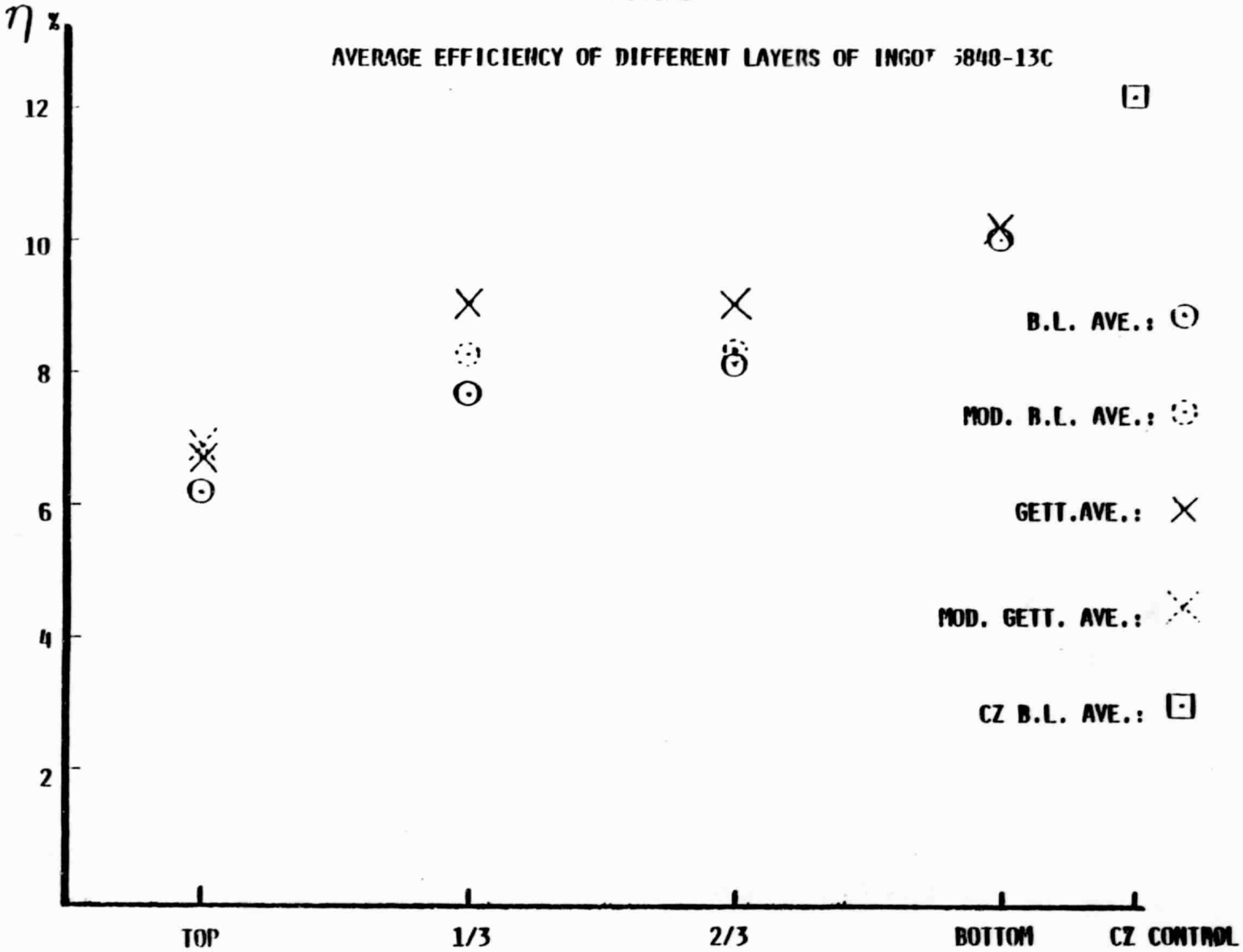
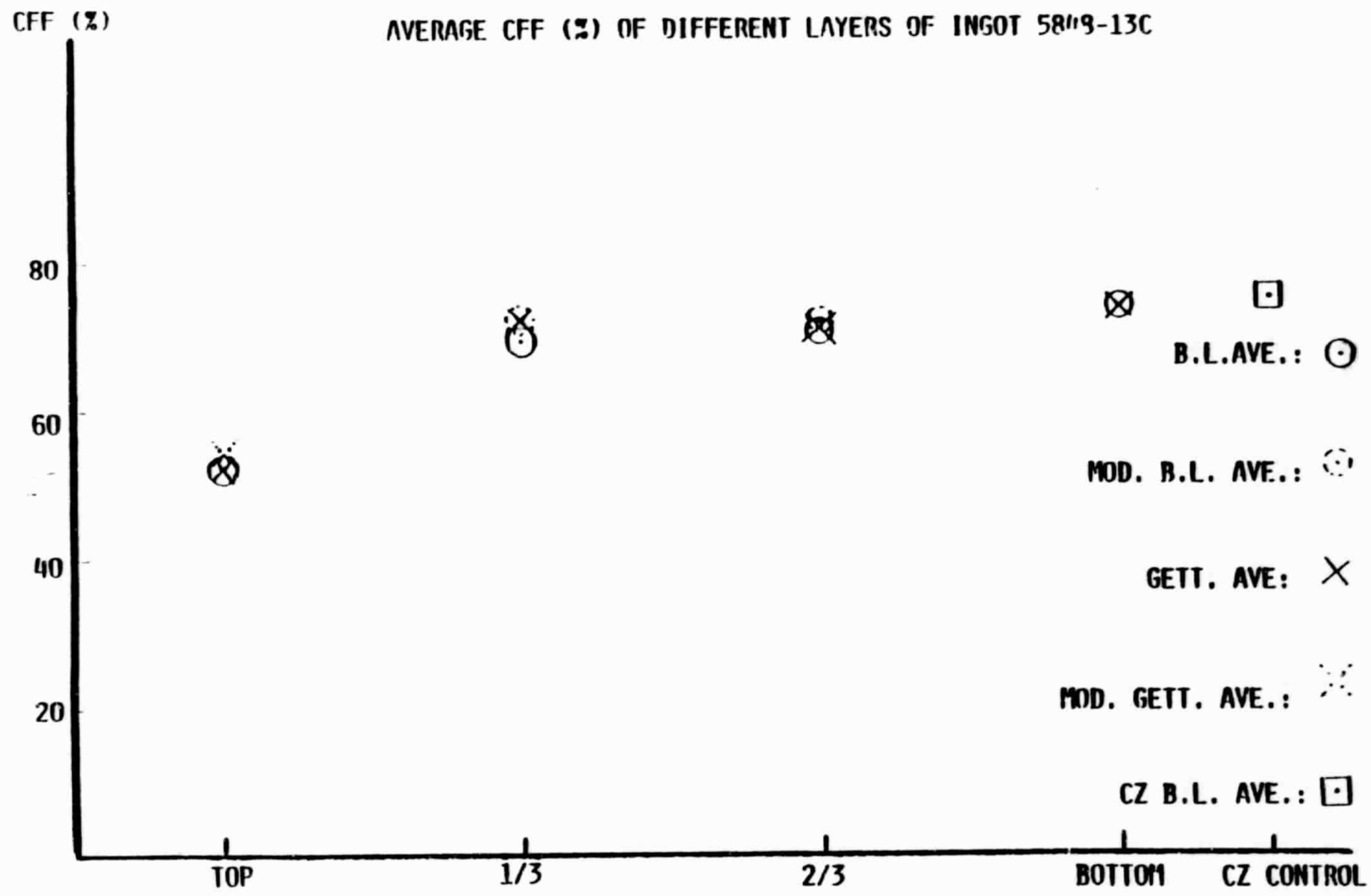


FIGURE 7

AVERAGE CFF (%) OF DIFFERENT LAYERS OF INGOT 5809-13C



ORIGINAL PAGE IS
OF POOR QUALITY

FIGURE 8

AVERAGE Voc OF DIFFERENT LAYERS OF INGOT 5848-13C

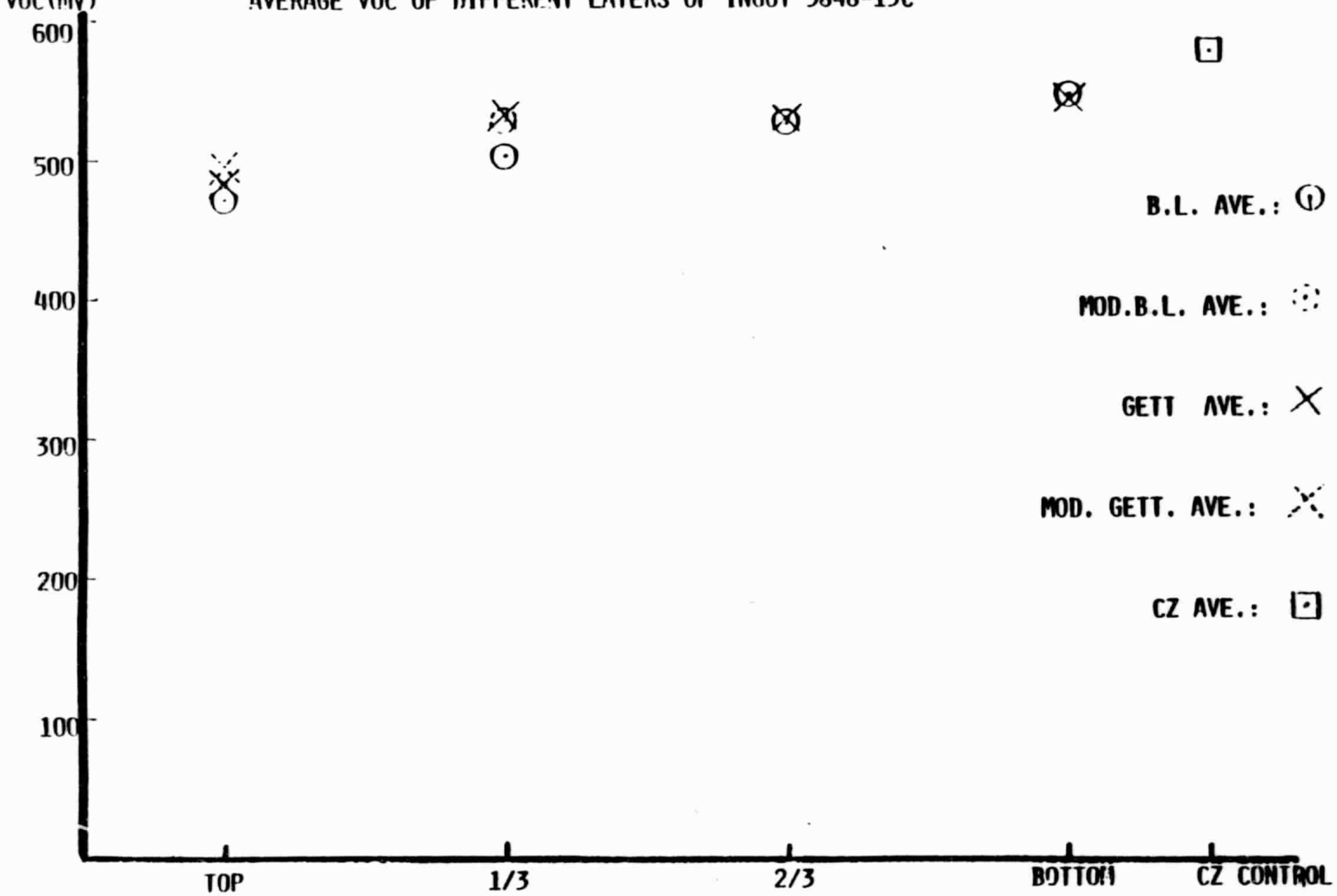
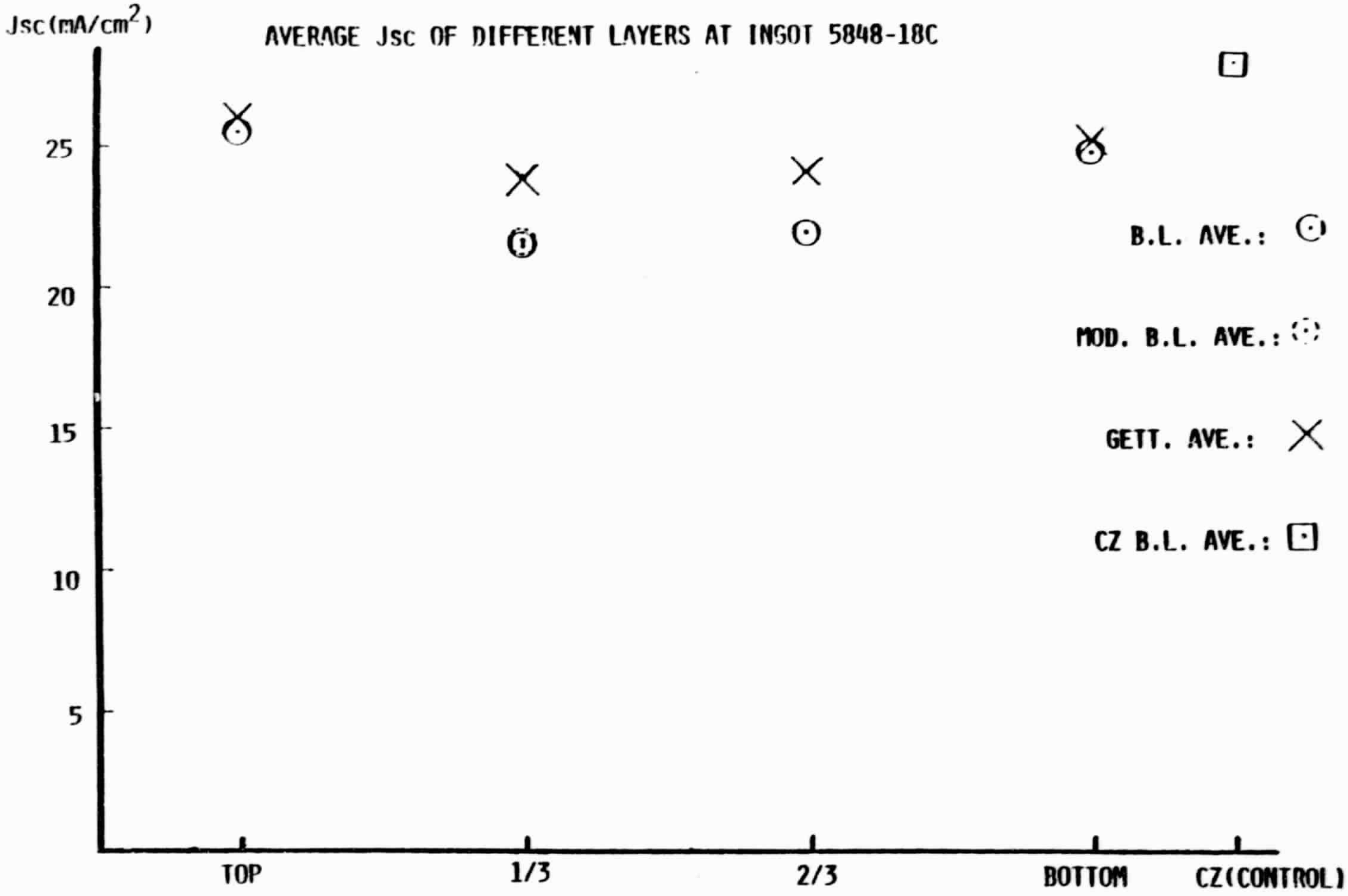


FIGURE 9



Jsc(mA/cm²)
AVERAGE Jsc OF DIFFERENT LAYERS AT INGOT 5848-18C
25
20
15
10
5
TOP
1/3
2/3
BOTTOM
CZ(CONTROL)
B.L. AVE.:
MOD. B.L. AVE.:
GETT. AVE.:
CZ B.L. AVE.:

FIGURE 10

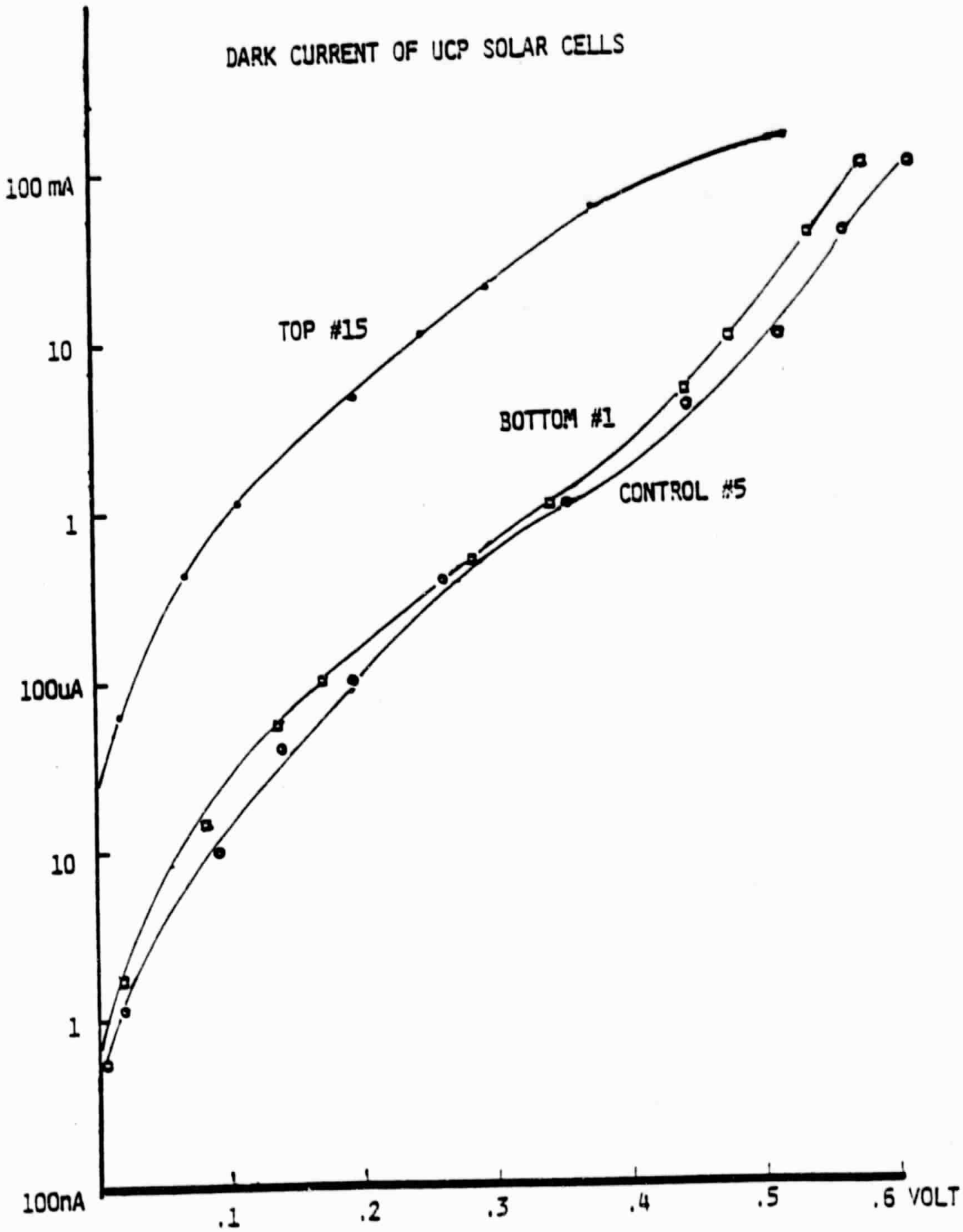

DARK CURRENT OF UCP SOLAR CELLS
100 mA
10
1
100uA
10
1
100nA
.1
.2
.3
.4
.5
.6 VOLT
TOP #15
BOTTOM #1
CONTROL #5

FIGURE 11

SPECTRAL RESPONSE OF SELECTED UCP BASELINE AND GETTERED CELLS FROM THE TOP OF INGOT #5848-13C

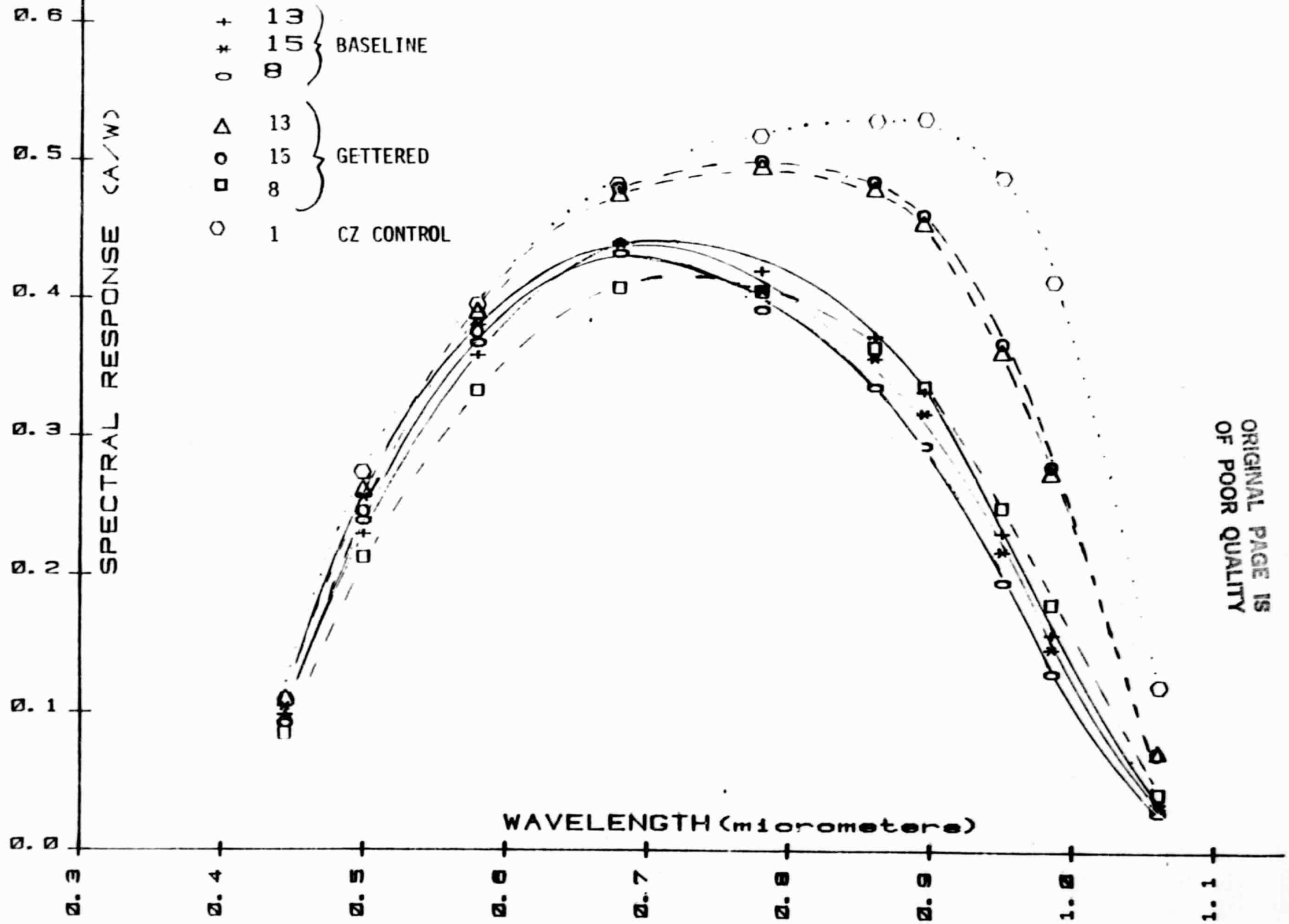


FIGURE 12

SPECTRAL RESPONSE OF SELECTED UCP BASELINE AND GETTERED CELLS FROM 1/3 OFF THE TOP OF INGOT #5848-13C.

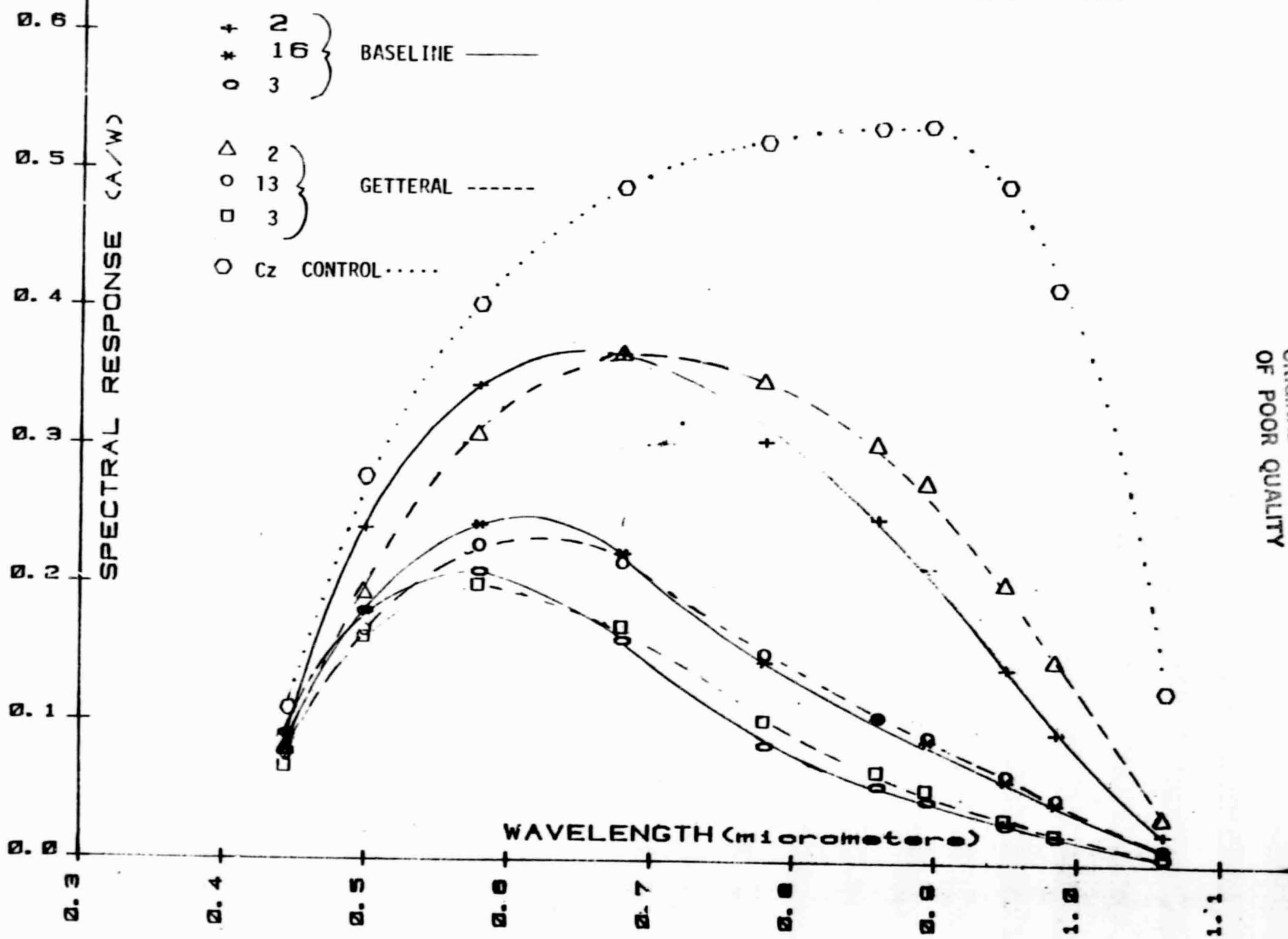


FIGURE 13

SPECTRAL RESPONSE OF SELECTED UCP BASELINE AND GETTERED

CELLS FROM 2/3 OFF THE TOP OF INGOT #5848-13C

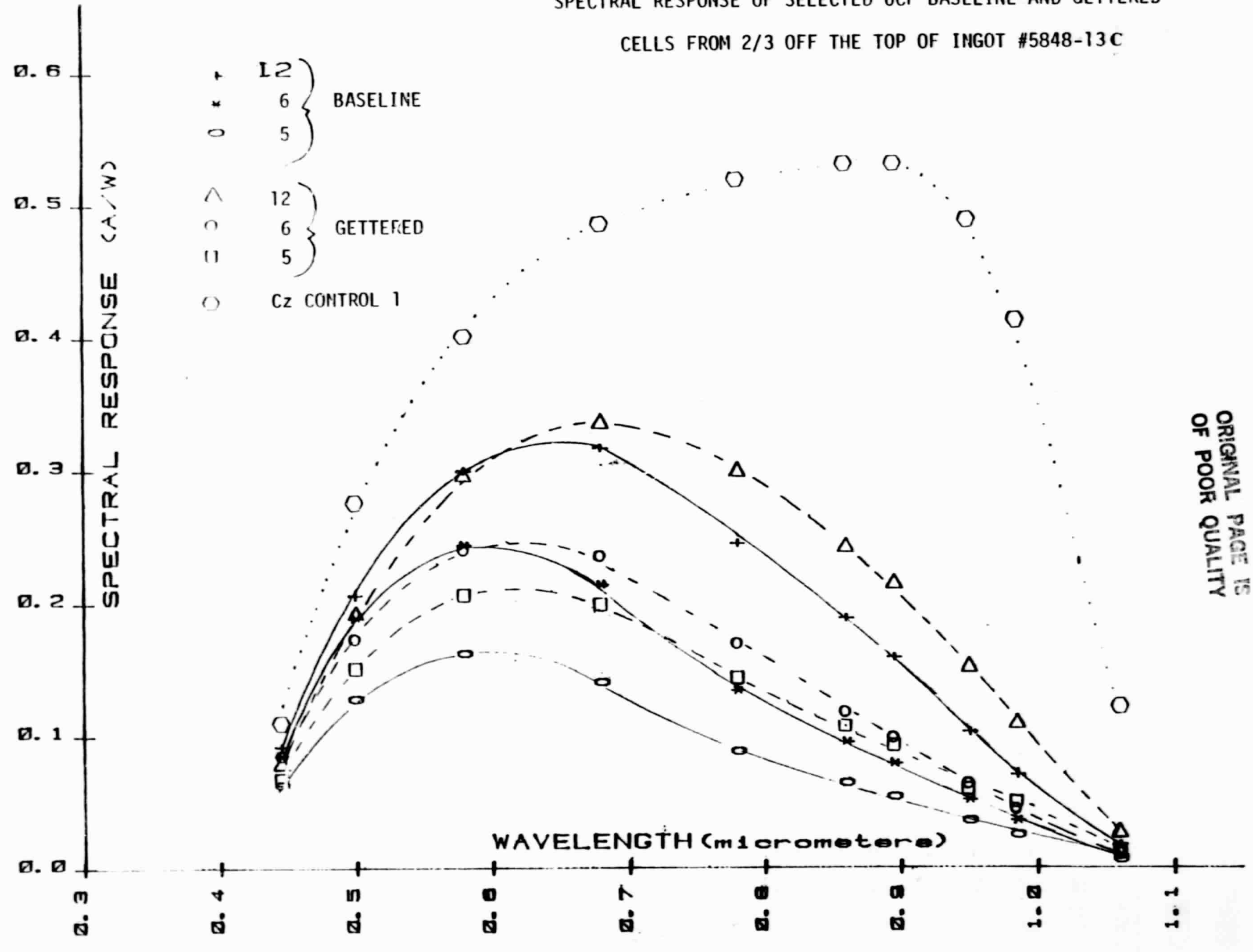
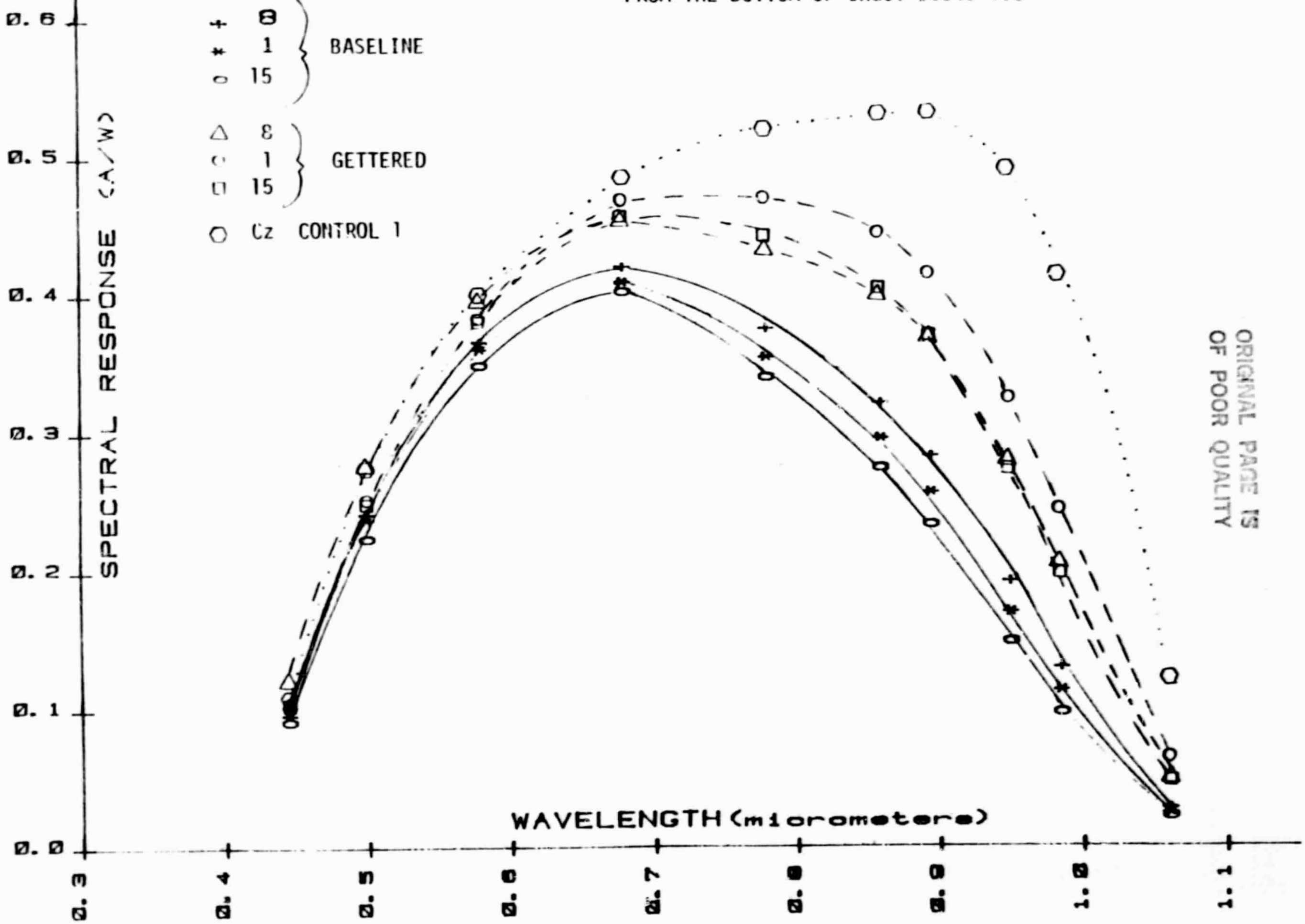


FIGURE 14

SPECTRAL RESPONSE OF SELECTED UCP BASELINE AND GETTERED

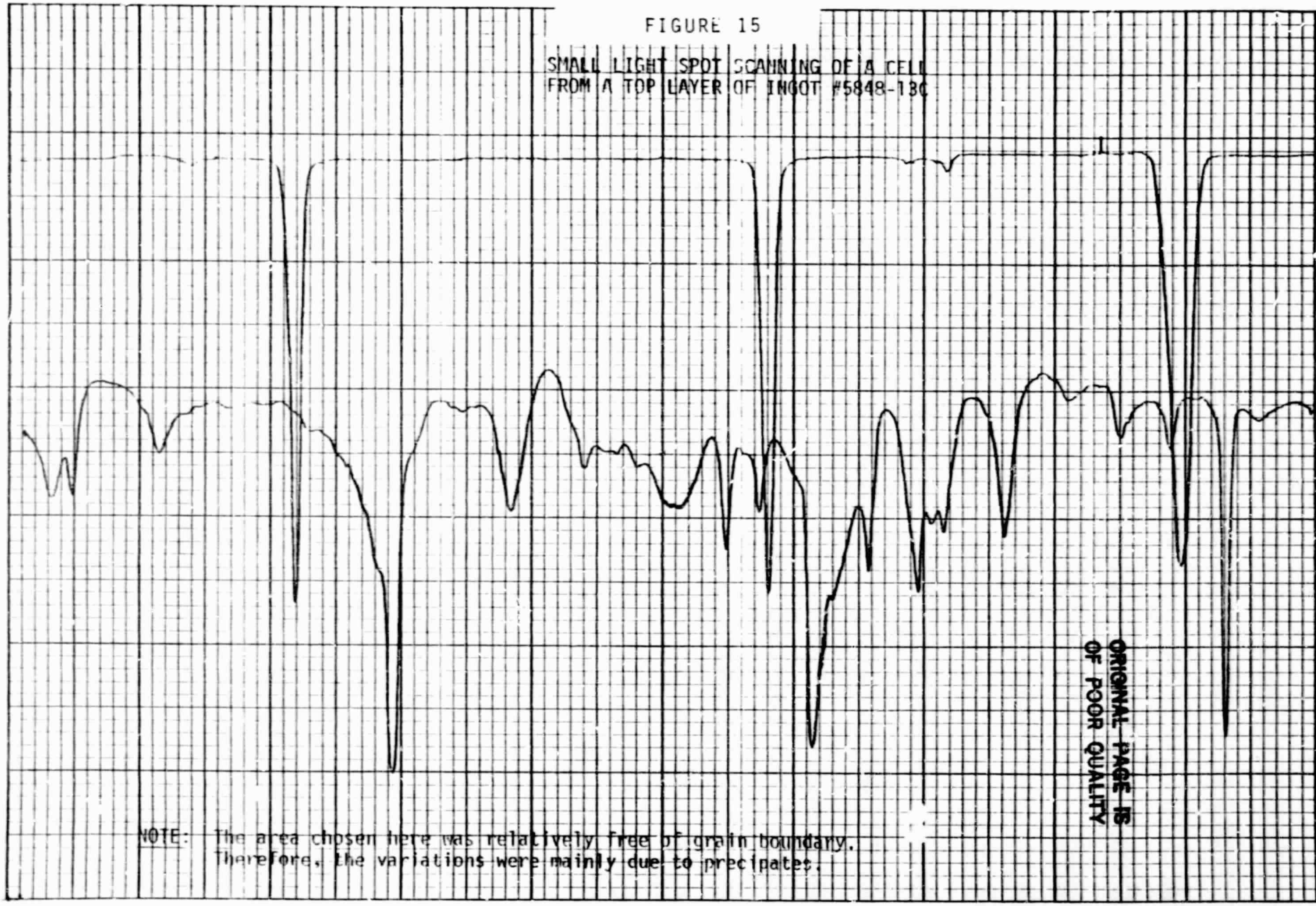
FROM THE BOTTOM OF INGOT #5848-13C



ORIGINAL PAGE IS
OF POOR QUALITY

FIGURE 15

SMALL LIGHT SPOT SCANNING OF A CELL
FROM A TOP LAYER OF INGOT #5848-13C



NOTE: The area chosen here was relatively free of grain boundary. Therefore, the variations were mainly due to precipates.

FIGURE 16

SMALL LIGHT SPOT SCANNING OF A CELL
FROM A MIDDLE LAYER OF INGOT #5848-13C

NOTE: The lower signal level than the previous Figure (11) here corresponded to a lower dsc and therefore a lower lifetime.

TABLE 8

SUMMARY OF RESULTS OF THE SOLAR CELLS FROM THE PARALLEL BASELINE AND GETTERING TEST FROM UCP INGOT #5848-13C

		Voc (mV)		Jsc (mA/cm^2)		CFF (%)		η (%)	
		Baseline	Gettered	Baseline	Gettered	Baseline	Gettered	Baseline	Gettered
Top	A V.	470	482	25.5	25.9	52	52	6.2	6.7
	S.D.	±40	±63	±.4	±.5	±.4	±.7	±1.0	±1.6
	Range	394-528	332-540	24.7-26.0	25.2-26.6	39-57	32-60	43-7.8	2.7-8.5
1/3	A V.	503	533	21.5	23.8	69	72	7.7	9.1
	S.D.	±98	±7	±1.9	±.7	±12	±2	2.2	±.5
	Range	164-544	522-548	18.5-24.7	22.6-24.7	26-75	68-75	0.8-9.6	8.3-
2/3	A V.	528	531	21.0	24.1	71	71	8.2	9.1
	S.D.	±12	±8	±1.4	±.9	±6	±2	±1.0	±.6
	Range	504-542	510-542	19.1-23.6	21.9-25.5	49-75	68-74	5.8-9.5	7.8-9.7
Bottom	A V.	550	25.3	24.9	25.3	74	74	10.1	10.3
	S.D.	±6	±.7	±.4	±7	±.1	±.1	±.3	±.5
	Range	540-558	24.1-26.7	24.2-25.5	24.1-26.7	72-76	71-76	9.6-10.7	9.4-11.1
CZ Control	A V.	582		28.1		75		12.3	
	S.D.	0		±.3		1		±.1	
	Range	582		27.6-28.3		74-76		12.1-12.4	

TABLE 9

ORIGINAL PAGE IS OF POOR QUALITY

MINORITY CARRIER DIFFUSION LENGTH OF SELECTED CELLS FROM INGOT 5848-13C

(PARALLEL BASELINE AND GETTERING TEST)

	BASELINE		GETTER PROCESS (875°C, ½ Hr)	
	CELL NO.	L_D (um)	CELL NO.	L_D (um)
TOP	1-2-8	30	1-4-8	61
	1-2-13	41	1-4-13	63
	1-2-15	36	1-4-15	68
1/3	2-9-2	26	2-10-2	61
	2-9-3	11	2-10-3	26
	2-9-16	26	2-10-16	34
2/3	3-9-5	18	3-10-5	40
	3-9-6	17	3-10-6	20
	3-9-12	23	3-10-12	48
BOTTOM	4-9-1	32	4-10-1	61
	4-9-8	36	4-10-8	56
	4-9-15	26	4-10-15	49
CZ CONTROL	1	163		
	3	165		
	5	163		

ORIGINAL PAGE IS OF POOR QUALITY

Table 10

SUMMARY OF SJ, BSF, AND MLAR SOLAR CELLS FROM

UCP INGOT 5848-13C

		Voc (mV)	Jsc (mA/cm^2)	CFF (%)	η (%)
Evaporated Al BSF (UCP - 12 Cells)	A V.	561	28.7	76	12.2
	S.D.	6	0.6	4	0.8
	RANGE	550-570	27.4-29.4	62-79	9.9-13.1
CZ Control (3 Cells)	A V.	593	32.6	78	15.1
	S.D.	1	0.2	1	0.2
	RANGE	592-594	32.4-32.8	77-79	14.9-15.3

		Voc (mV)	Jsc (mA/cm^2)	CFF (%)	η (%)
Al Paste BSF UCP (12 Cells)	A V.	553	29.3	61	9.9
	S.D.	11	0.7	10	1.9
	RANGE	530-564	28.4-30.3	40-71	6.2-11.6
CZ Control (4 Cells)	A V.	596	33.4	69	13.7
	S.D.	3	0.3	3	.8
	RANGE	592-600	33.2-33.9	67-73	13.1-14.9

were used for cells (to minimize incomplete alloying due to lower temperatures on the boat surface). However, this did not prevent the severe shunting observed. More tests are needed to determine the causes of shunting.

4.0 Test Of More Severe Gettering (With HEM As Comparison)

From Figure 9, it is obvious that Jsc improved and the gap between the middle layers and the other layers narrowed after gettering. Therefore, it would be interesting to see whether more severe gettering would improve Jsc and narrow the gap further. Since cell results were relatively uniform within the wafers, only two wafers, one from each middle layer, were used in preliminary tests for further gettering. Each wafer was divided into four portions and for each portion a different gettering step was applied. The four steps were baseline (no gettering), $875^{\circ}C/½$ hour, $875^{\circ}C/1$ hr., and $950^{\circ}C/1$ hr., for both wafers. Also, in order to separate the effects of the heat treatments in the gettering processes one cell in each group was covered with CVD SiO_2 to protect against gettering diffusion, but went through the heat treatment cycles with the other cells. After the gettered layers were etched off, baseline processes were applied to fabricate cells. Table 11 shows the average Jsc as a function of gettering treatment. Both wafers had similar performance. There was a marked increase in Jsc as the gettering was more severe. Comparing with Table 7, the Jsc of the the more severely getterea cells had exceeded the best cell in baseline process. Also, surprisingly the Jsc of the cells covered with SiO_2 also increased even though less than the gettered samples. The cause of this could be internal gettering by oxygen precipates or the SiO_2 layer could have had a gettering effect. Spectral response of selected cells from this test are given in Figure 17 and diffusion lengths of selected cells are listed in Table 12. These results show a gradual improvement for more severe gettering. However, Figure 17 seems to

show that some gettered cells had a better long wavelength response than the control. (Also better diffusion length from Table 12). This is not seen in the Jsc value. Since these measurements (spectral response, Ld) were made in the dark at low light levels, it indicates a possible light bias effect.

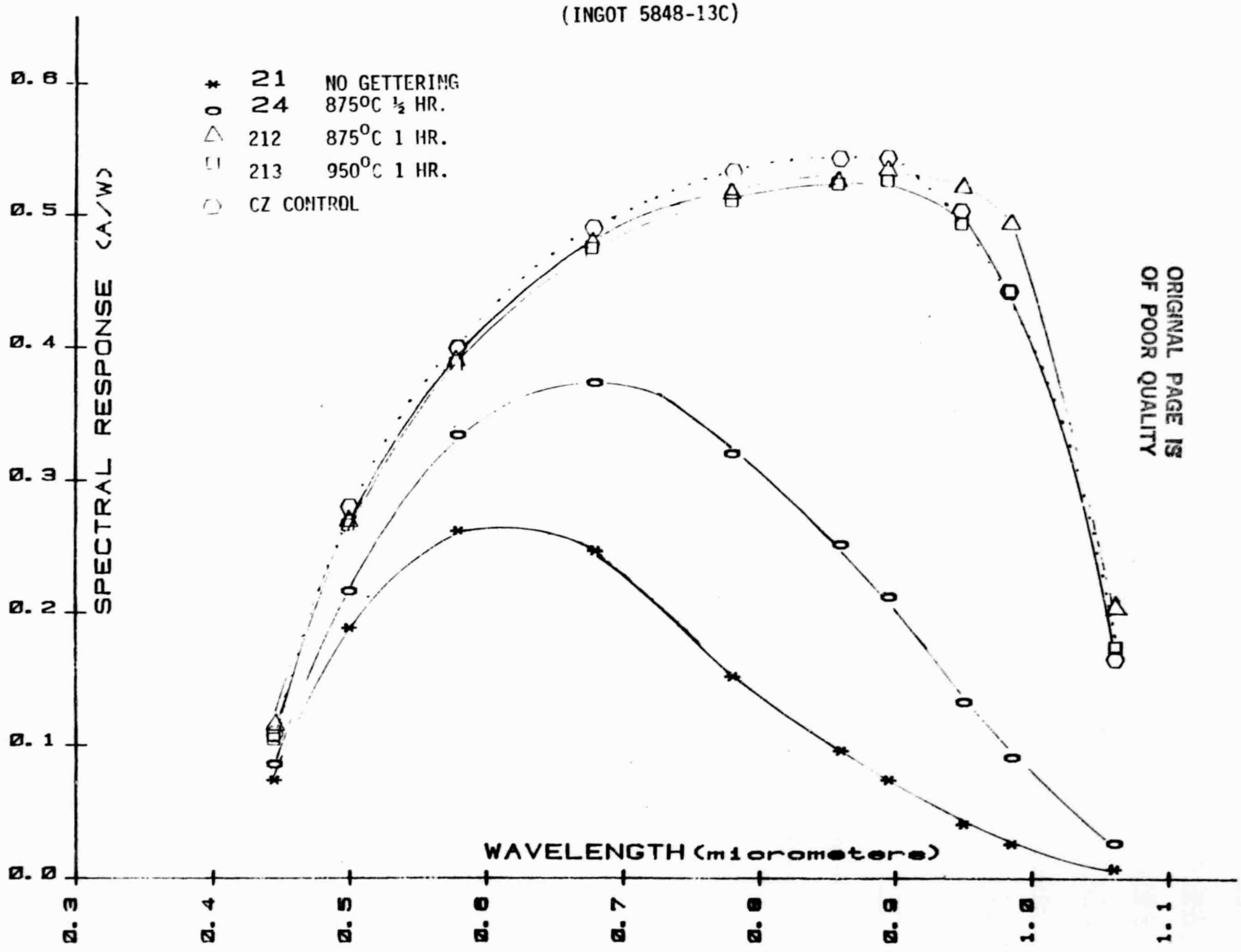
Even More Severe Gettering

In order to see whether the gettering limit had been reached in the previous test, a 1050°C one hour gettering was applied to additional material from the middle portion of the UCP ingot 5848-13C. After the gettered junction was etched away, a baseline process was applied to fabricate cell. As before, one cell was protected with CVD SiO_2 during gettering diffusion to test the effect of the heat cycle itself. The results are summarized in Table 13. Comparing Table 11 the average Jsc after the 1050°C gettering is not better than that of the 950°C gettering, therefore, a saturation of Jsc on ribbon cells might have reached, even though the Jsc is still lower than the CZ control.

HEM Silicon

For comparison of gettering effects, selected wafers from HEM ingots 4141 C and 4148 (see Annual Report Phase III Reference (1)) were also used in the 1050°C gettering test. The average Jsc of the resultant gettered cells were listed along with the average baseline Jsc of corresponding material in the same portions of the ingots in Table 3, and no significant improvement was observed after gettering. It may be that an impurity that is present in the middle layers of the UCP ingot 5848-13C, is not present in either of the HEM ingots.

FIGURE 17: SPECTRAL RESPONSE OF SELECTED UCP SOLAR CELLS FROM THE MORE SEVERE GETTERING TESTS (INGOT 5848-13C)



ORIGINAL PAGE IS OF POOR QUALITY

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE 11

SUMMARY OF Jsc FROM SOLAR CELLS

FROM THE MORE SEVERE GETTERING TESTS

(UCP INGOT #5848-13C)

Gettering Treatment	Wafer	Ave. Jsc (mA/cm^2)	Jsc* of The Cell Covered With SiO_2
None	1/3 2/3	22.5 23.7	- -
875°C ½ Hr.	1/3 2/3	24.6 24.3	24.7 24.8
875°C 1 Hr.	1/3 2/3	25.5 26.3	25.2 24.4
950°C 1 Hr.	1/3 2/3	27.0 26.3	24.8 25.9
CZ Control (No Treatment)		28.5	-

*Jsc of the cell covered with CVD SiO_2 during gettering diffusion.

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE 12

MINORITY CARRIER DIFFUSION LENGTH OF SELECTED UCP SOLAR CELLS FROM THE MORE SEVERE GETTERING TESTS (INGOT #5848-13C)

Cells #	L_D +(um)	Remarks
2-1	13	No Gettering
2-4	34	875° ½ Hr.
2-8 (Covered)*	34	
2-13	199	875°C 1 Hr.
2-9 (Covered)*	121	
2-12	235	950°C 1 Hr.
2-15 (Covered)*	129	

+ L_D was measured in the dark.

* "Covered" means the cell was covered with CVD SiO_2 during gettering diffusion.

TABLE 13

SUMMARY OF RESULTS FOR SOLAR CELLS GETTERED AT 1050°C FOR
1 HOUR FROM UCP INGOT 5848-13C

		Voc (mV)	Jsc (mA/cm^2)	CFF(%)	η (%)
1050°C 1 Hr.	AVE.	541.0	262	70	10.0
(11 Cells)	S.D.	$\pm$ 7	$\pm$0.8	$\pm$2	$\pm$0.4
	RANGE	530-552	24.7-27.2	60-72	9.3-10.8
CELL PROTECTED BY CVD SiO_2		540	25.9	71	9.9
	AVE.	584	28.2	77	12.7
CZ CONTROL (3 CELLS)	S.D.	$\pm$2	$\pm$.3	$\pm$3	$\pm$.4
	RANGE	582-586	27.8-28.4	74-80	12.3-13.0

TABLE 14

A COMPARISON OF Jsc FROM HEM CELLS GETTERED AT 1050^{o}C FOR ONE HOUR WITH HEM BASELINE CELL FROM CORRESPONDING AREAS.

INGOT #	BASELINE Jsc	GETTER Jsc
41-41C	25.6	26.3
41-48	27.6	28.1

5.0 Light Biased Diffusion Length Measurements On The Severely Gettered Solar Cells

As mentioned above, from preliminary spectral response and minority carrier diffusion length (L_D) measurements, (made without light bias), following more severe getter cycles, there were large improvements in red response and diffusion lengths; in some cases the values increased to be comparable to CZ control. Jsc also improved substantially but not to the same extent so that the Jsc of these gettered cells was always lower than Jsc for the CZ controls. This suggested a light biased effect that reduced the effective diffusion length in the UCP Si but did not affect the CZ control. To test this possibility, a low frequency chopper was used with a lock-in amplifier (as opposed to the unbiased D.C. measurements usually made). Two separate lamps were used as the biased light source. In preliminary tests, bias was provided by a regular desk lamp which had a maximum light intensity on the sample roughly equivalent to about .05 sun (light intensity was measured by the Jsc of a CZ control cell adjacent to the test sample). Further bias tests used a tungsten lamp with light intensity adjusted to ~ 1 sun. In the latter case with higher intensity, only a small gain could be used to amplify the current signal because of the strong bias current on the available operational amplifier. In many cases, a 1 ohm resistor was used for convenience. Therefore, the signal to noise ratio was not as high as for regular D. C. (dark) or the preliminary low bias light measurements. Nevertheless, the effects of the biased light were such that they were observable even with lower S/N ratio. Table 15 shows the results of the measurements (it also includes some results of dark L_D measurements from Table 12). One can see that the light-biased L_D values were much lower than the dark L_D in the more severely gettered samples while in the ungettered or lightly gettered samples, the light-biased L_D values were larger. The last column shows the results of

measurements in the dark just after the light biased measurements, using the same instrumentation. The results were very close to that of the dark D.C. L_D measurements routinely taken earlier (the 1st column) and they showed that the new measurements were valid. Also since the measurement only took a few minutes to finish and were made immediately after the light biased measurement on each sample, it showed that the light biased effect, (either degradation or enhancement) recovered soon after light was removed. That is different from the light degradation effect reported earlier by Cheng et. al. (Reference 4) where the effects recovered only after a longer period of time. These present light bias effects help to explain why the Jsc did not improve as much as the dark L_D measurement seemed to indicate.

In addition, some light biased spectral response readings were taken. Qualitatively, these curves showed similar effects to the light biased L_D measurements.

Since the more severe gettering test was performed only on the middle layers where gettering effects were most pronounced, the light biased data referred only to these layers. In order to have a more complete picture of the light biased effects, measurements were done on selected baseline cells, and cells gettered at 875°C for 30 min., from all layers. The results are listed in Table 16. The results of previous non-biased measurements are also included for comparison. One can see a fairly strong positive light biased effects on all layers of the crystal (compare L_{D1}, with L_{D2}) and the effects were recovered within minutes after the biased light was turned off (L_{D3}). The light biased effect was the opposite to the results for more severely gettered cells, but consistent with the lightly gettered cells. The light biased results were not

accurate enough for detailed comparison, but were indicative of the existence of such effects.

HEM Silicon

As mentioned above, the same gettering cycles as used on the UCP Si had little effect on the HEM samples. Both DC dark L_D and .05 Sun-biased L_D measurements were performed on selected samples of the gettered HEM Si cells. The results are listed in Table 17. The resultant dark L_D - values were within range of the L_D - values of previous baseline cells (see Reference 1). No severe light bias effect could be inferred from these measurements.

Table 15

ORIGINAL PAGE IS OF POOR QUALITY

RESULTS OF LIGHT BIAS MINORITY

CARRIER DIFFUSION LENGTH STUDY ON GETTERED

UCP CELLS

PROCESS	CELLS #	L_{D1} (µm) D.C. DARK	L_{D2} (µm) 0.05 SUN	L_{D3} (µm) 1 SUN	L_{D4} (µm) DARK AFTER LIGHT TURN OFF
Baseline	2-1	13	19	20	14
8.75°C ½ Hr. Gettering	2-4 2-8*	34 34	52 41	72 —	35 —
875°C 1 Hr. Gettering	2-13 2-9*	199 121	77 72	85 —	175 —
950°C 1 Hr. Gettering	2-12 2-15*	235 129	108 58	85 —	209 —
1050°C 1 Hr. Gettering	2-12 2-9*	275 135	141 74	82 96	317 143
CZ Control	1	188	190	195	171

* Cells were covered with SiO_2 during gettering diffusion (See 28th Monthly Report).

TABLE 16

RESULTS OF LIGHT BIAS L_D MEASUREMENTS ON SELECTED CELLS ON UCP INGOT 5848-13C

BASELINE				GETTERED (875^0C ½ Hr.)			
CELL NO	L_{D_1} (DARK D.C.)	L_{D_2} (1 SUN)	L_{D_3} (DARK)	CELL NO	L_{D_1} (DARK D.C.)	L_{D_2} (1 SUN)	L_{D_3} (DARK)
1-2-13	41	71	36	1-4-13	63	90	77
2-9-2	26	88	32	2-10-2	61	91	72
3-9-12	23	72	35	3-10-12	48	74	47
4-9-8	36	83	33	4-10-8	56	99	56

NOTE: L_{D1} is the original D.C. dark L_D.

L_{D_2} is the 1 Sun bias L_D

L_{D3} is the Dark L_D Measured right after the biased lamp was turned off.

Table 17

MINORITY CARRIER DIFFUSION LENGTH OF

1050°C 1 HR GETTERED HEM CELLS

CELLS NO.	L_D (μm) (DARK D.C.)	(L_D (μm) (0.05 SUN)
4-1	121	108
4-2*	139	130
4-6	160	140
6-1	62	77
6-4*	111	132
6-5	56	64

* Cells were covered with SiO_2 during gettering diffusion. (See 28th Monthly Report).

C. Solar Cells From UCP Ingot C-4-21A

UCP Ingot C4-21A was 3 61/64 x 3 61/64 x 4 3/32 in^3 and weighted 2.49 kg. It was a quarter of a larger ingot. Figure 18 shows both where the quarter ingot was cut and where 2x2cm^2 cells were made on individual wafers (16 2x2cm^2 cells per wafer). The slicing was similar to ingot 5848-13C. The grain structure of this ingot is such that, at the bottom of the ingot, around the corner of the center of the original larger ingot (as shown in Figure 1), there is a region of relatively finer grains (a few millimeter range) which occupies 40-50% of the total area. Outside of the region the grain size is large (centimeter range). However, this finer grain region "grows" in size as we move from the botton to top and at the top it occupies 70% of the total area. At the top, the average grain size in the finer grain region also increases slightly.

Two wafers from each of the four (4) positions being cut were used for cell fabrication. One was used for direct baseline processing while the other was $POCl_3$ gettered (½ hr. at 875°C) followed by the baseline processing after the gettered glass was etched away, similar to Section B 1.0. The results of the experiment are summarized in Table 18 and Table 19, for the baseline and gettered cells respectively. In these tables an extra column was added to summarize the short circuit current of the cells in the larger grain area from layer 1/3 down to the bottom (i.e. cells outside of the finer grain regions mentioned above). It can be seen that these cells did not have higher Jsc than the total average. From Table 17, the efficiency, Jsc and CFF of the cells of the baseline process on the top half of the ingot seems to be superior and the lower half of the ingot seems to deteriorate slightly downward. However, from Table 2, all these parameters of the gettered cells seem to be similar through

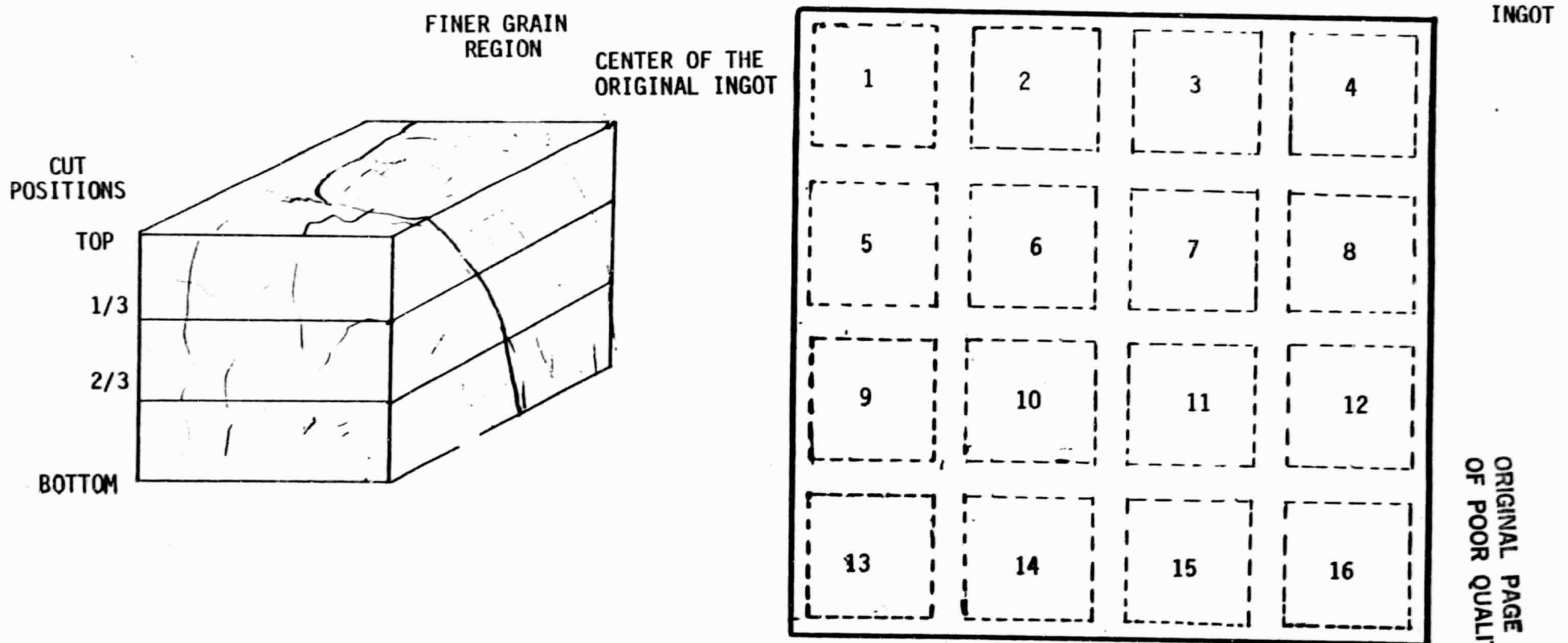
the whole ingot. This seems to indicate that the gettering process had cleaned-up the bottom half of the ingot.

Minority Carrier Diffusion Length

Dark D.C. minority carrier diffusion lengths of selected solar cells were measured and they are listed in Table 20. In general, the top half of the ingot is still superior even after gettering, but the diffusion lengths of the bottom half improved to a range where difference of diffusion lengths did not influence solar cell performance as much as the non-gettered samples.

FIGURE 18

INGOT C-4-21A



ORIGINAL PAGE IS OF POOR QUALITY

ORIGINAL PAGE IS OF POOR QUALITY

TABLE 18

SUMMARY OF BASELINE RESULTS OF

INGOT C-4-21A

		Voc(mV)	Jsc (mA/cm^2)	CFF(%)	η(%)	(#1,5,9,13-16 Large Grain Area) Jsc (mA/cm^2)
TOP	AVE.	553	26.3	75	11.0	
	S.D.	± 7	± 0.8	± 1	± 0.4	
	RANGE	542-570	25.1-28.0	72-78	10.2-11.9	
1/3	AVE.	557	26.9	75	11.2	26.7
	S.D.	± 7	± .6	± 2	± .5	± .7
	RANGE	548-568	25.6-28.3	71-77	10.3-12.2	25.6-27.8
2/3	AVE.	556	26.4	73	10.7	26.3
	S.D.	10	± .6	± 14	± 1.4	± 1.5
	RANGE	530-572	25.4-27.5	45-78	6.0-11.7	25.4-26.9
BOTTOM	AVE.	549	25.7	72	10.2	25.9
	S.D.	29	± .8	± 12	± 2.0	± .6
	RANGE	422-566	24.4-26.9	26-77	28-11.4	25.3-26.9
CZ CONTROL	AVE.	584	[illegible]	77	13.0	
	S.D.	± 2	± 0.28	± 1	± 0.2	
	RANGE	580-586	28.8-29.4	75-77	12.6-13.1	

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE 19
875°C ½ Hr. GETTERED AND THEN
BASELINE RESULTS OF INGOT C-4-21A

		Voc(mV)	Jsc (mA/cm^2)	CFF(%)	η (%)	(#1,5,9,13-16 Large Grain Area) Jsc (mA/cm^2)
TOP	AVE.	556	27.0	76	11.4	
	S.D.	± 11	± 0.8	± 1	± 0.6	
	RANGE	530-572	24.8-28.5	74-78	9.9-12.4	
1/3	AVE.	560	26.8	76	11.4	26.7
	S.D.	± 5	± 0.6	± 1	± 0.3	± 0.6
	RANGE	552-570	25.8-27.9	73-78	10.9-11.8	
2/3	AVE.	563	26.9	76	11.4	26.7
	S.D.	± 6	± 0.5	± 2	± 0.4	± .4
	RANGE	548-574	26.0-27.5	68-78	10.5-12.1	26.1-27.4
BOTTOM	AVE.	561	26.5	76	11.3	26.8
	S.D.	± 8	±0.6	± 1	± 0.6	± 0.2
	RANGE	542-572	25.5-27.0	73-77	10.3-11.9	26.5-27.0

NOTE: Same Control in Table will be applied.

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE 20

MINORITY CARRIER DIFFUSION LENGTH OF SELECTED CELLS FROM INGOT C-4-21A

	BASELINE		GETTER PROCESS (875°C ½ HR.)	
	CELL NO.	L_D(um)	CELL NO.	L_D (um)
TOP	1-4-3	96	1-5-3	103
	1-4-11	39	1-5-11	32
1/3	2-10-8	69	2-11-12	109
	2-10-5	41	2-11-13	62
2/3	3-10-10	59	3-11-4	67
	3/10/8	55	3-11-13	55
BOTTOM	4-12-10	57	4-11-14	73
	4-12-2	31	4-11-2	37
CZ CONTROL	5	173		

ORIGINAL PAGE IS OF POOR QUALITY

D. Comparison Of The Three Available Cast Materials

1.0 Baseline Test

In order to compare the three cast silicon materials (UCP, HEM Silso) which are now available commercially either in the wafer form (HEM and Silso) or as finished solar cell form (UCP), selected wafers from all three materials were processed together to fabricate solar cells. For UCP Si, wafers from random sources were used (i.e. not from any known ingot). The 10cm x 10cm wafers used had relatively uniform grain size. For HEM Si, wafers from ingot 4141C were used, this ingot was studied earlier (see Phase III Annual Report). This ingot is relatively free from excessive participates or impurity problem and is more representative of present HEM silicon. The HEM wafers used were about 7.5cm x 10cm in size. They included one single crystalline piece and three polycrystalline pieces. As for the Silso Si, commercially available $10 \times 10 cm^2$ wafers were used. Three typical grain structures were identified for these new Silso wafers as compared to only one in the older Silso. That was because the new Silso wafers were cut from larger ingots. One structure was long grain structure with grain length in the centimeter range, but width only in range of 1-5mm. One was medium grain structure with grain dimension in the range of a few millimeters, and lastly, there was a fine grain structure with grain dimension of sub millimeter range. Since the proportion of each kind in the complete ingot is unknown, a wafer of each of the grain structure was used in the study. A number of $2 \times 2 cm^2$ cells (16 per $10 \times 10 cm^2$ wafers and 12 per $7.5 \times 10 cm^2$) was fabricated by the baseline process together. The results are summarized in Table 21. The UCP material varied only slightly from wafer to wafer for they were of similar grain structure. As for the Silso material, results varied from structure to structure with the medium grain structure giving the best results. Even though the long grain structure had the largest grain size, the smallest

grain dimension (i.e. the width of the grain) was comparable to the medium grain structure. It also indicated that grain size was probably not the only factor to determine cell performance. As for HEM, the single crystal wafer produced the best results while most of the polycrystal ones were only slightly lower, except the wafer from the bottom of the ingot which had lower performance. Cells made for the three materials were fairly similar in overall performance.

Minority Carrier Diffusion Length

Minority carrier diffusion lengths were measured on selected samples (a good cell and a bad cell were chosen from each wafer) and the restuls are listed in Table 22. One can see that wafer J (single crystal HEM) has higher L_D's while wafer F (fine grain Silso) and wafer G (bottom of HEM ingot) had lower L_D. They are consistent with the baseline results.

2.0 Gettering Test

To continue the comparison of the three materials, a severe gettering test (1 hr. 950°C) was applied to selected wafers from all three cast materials. The temperature and time were chosen because they were the optimal temperature and time when the more severe gettering test was applied to UCP ingot 5848-13C (see Section B 3.). Then after the gettering glasses were etched away, baseline process was applied to fabricate $2x2cm^2$ cells.

The resultant Jsc is listed in Table 23 with corresponding baseline Jsc values from similar wafers from previous experiments.

For the Silso material, only the fine grain wafer showed a significant gain while the long grain wafer had a small gain from the gettering process. The medium grain cells had no gain.

For UCP material, both the wafer from the bottom of C4-21A ingot and the wafer randomly chosen from unknown ingot showed a moderate gain. The gain of the wafer from the bottom of C4-21A did not exceed the gain from a much lighter gettering (½ Hr. 875°C) as shown in Section C.

Finally, the HEM showed no gain at all consistent with previous results (Section B-4). These results seem to indicate that only a moderate amount of improvement can be expected from a gettering process in all three materials. If there are residual impurities, they are not easily moved.

3.0 High Efficiency Processes

High efficiency processes including shallow junction (SJ), narrow grid lines, evaporated Al p+ back (800°C 15 min. alloying) and MLAR were applied to selected samples from the three materials. The results are summarized in Table 24. The motivation of using evaporated Al instead of the more common Al paste BSF was to eliminate shunting problems, which the paste had on 1-3 ohm material. It apparently works fairly well for most cells except HEM. The HEM single crystal samples which had the best baseline result (see Section D-1) had shunting problems in the high efficiency solar cells and low average CFF. The shunting is probably related to the Al back process. However, the best HEM cell (14.4%) is still better than all the cells except CZ controls. The SILSO and UCP cell all had respectable performances as shown in Table 24. Therefore, except for the process-related problem in HEM, all the materials had shown similar promise for up-graded processes.

TABLE 21

SUMMARY OF RESULTS OF BASELINE CELLS FOR COMPARING THREE CAST SI MATERIALS

		Voc(mV)	Jsc(mA/cm^2)	CFF(%)	η(%)
UCP					
A	AVE.	514	25.6	74	10.1
	RANGE	20-550	24.4-26.1	25-78	0.1-11.2
B	AVE.	555	25.8	76	10.9
	RANGE	534-568	24.1-27.0	68-79	8.8-12.1
C	AVE.	550	25.3	72	10.1
	RANGE	512-564	24.4-26.5	38-79	4.8.11.8
UCP OVERALL	AVE.	539	25.6	74	10.4
	RANGE	20-568	24.1-27.0	25-79	0.1-12.1
SILSO					
D(Long Grain)	AVE.	552	24.4	72	9.8
	RANGE	526-564	21.6-26.6	46-79	6.1-11.3
E (Medium Grain)	AVE.	556	26.2	76	11.1
	RANGE	552-564	25.4-27.0	72-78	10.1-11.6
F(Fine Grain)	AVE.	547	23.7	75	9.7
	RANGE	536-552	22.6-24.4	61-78	7.9-10.5
SILSO OVERALL	AVE.	552	24.7	74	10.2
	RANGE	526-564	21.6-27.0	46-79	6.1-11.6
HEM					
G(Single Crystal)	AVE.	579	27.7	73	11.7
	RANGE	574-588	26.9-28.5	66-79	10.1-13.2
H(Poly)	AVE.	566	26.7	76	11.5
	RANGE	552-576	25.4-27.5	70-78	10.3-12.2
I(Poly)	AVE.	564	26.6	74	11.1
	RANGE	550-574	25.0-27.6	67-78	9.7-12.1
J(Poly)	AVE.	551	24.8	74	10.1
	RANGE	538-560	23.6-25.5	65-78	8.5-11.0
HEM OVERALL	AVE.	565	26.5	74	11.1
	RANGE	538-588	23.6-28.5	65-79	8.5-13.2
CZ CONTROL	AVE.	586	29.0	77	13.1
	RANGE	586-586	28.8-29.3	76-77	12.9-13.3

TABLE 22

MINORITY CARRIER DIFFUSION LENGTH OF SELECTED SAMPLES FOR THE THREE CAST MATERIALS

		CELL #	L_D (um)
UCP	Poly Si	A-7	61
		A-10	64
		B-7	84
		B-16	58
		C-12	59
		C-15	38
Silso	Long Grain	D-2	37
		D-6	82
	Med.Grain	E-1	34
		E-15	95
	Fine Grain	F-13	18
		F-15	37
HEM	Single Crystal	G-1	170
		G-12	87
	Poly Si	H-8	92
		H-12	35
		I-1	42
		I-10	87
		J-1	46
		J-10	31
CZ CONTROL		#4	212

NOTE: Fromeachwafer,agoodcellandabadcellwerechosen.

TABLE 23

COMPARISON OF AVERAGE Jsc OF GETTERED (1 Hr. 950°C) CELLS WITH CORRESPONDING BASELINE CELLS FOR THE THREE CAST MATERIALS

		AVERAGE Jsc (mA/cm²) Baseline	AVERAGE Jsc (mA/cm²) Gettered
SILSO	Long Grain	24.4	24.9
	Medium Grain	26.2	25.9
	Fine Grain	23.7	24.8
UCP	(4-21A) Bottom Layer	25.7	26.7
	Random	25.6	26.4
HEM		25.9	26.1

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE 24

HIGH η CELLS (WITH SJ p^+ BACK AND MLAR)

UCP, SILSO AND HEM

			Voc (mV)	Jsc (mA/cm^2)	CFF (%)	η (%)
UCP	INGOT # (C4-21A)	AVE. S.D. RANGE	553 19 508-576	29.9 0.8 28.8-31.3	77 5 64-80	12.7 1.2 9.9-13.9
	RANDOM	AVE. S.D. RANGE	554 7 542-558	29.7 0.6 28.8-30.4	78 1 76-80	12.9 0.3 12.3-13.3
SILSO	(MEDIUM GRAIN)	AVE. S.D. RANGE	564 7 554-574	29.9 0.5 29.4-30.8	78 1.3 76-80	13.1 0.4 12.6-13.6
HEM	(SINGLE CRYSTAL)	AVE. S.D. RANGE	555 39 478-594	31.4 0.5 30.9-32.3	54 18 31-77	9.6 4.0 4.6-14.4
CZ CONTROL		AVE. S.D. RANGE	597 3 588-596	32.5 0.9 31.4-33.7	77 3 73-80	14.7 0.7 13.7-15.5

E. **Solar Cells From Fast Growth EFG Ribbons**

The 17-200 Series

Fast growth (3.8cm/min) and 10cm wide) EFG ribbons were grown with various conditions at Mobile Tyco. Only four cells were fabricated for each 10cm x 5cm ribbon (or 2 per 5x5cm^2 in some cases). For the ribbons grown with CO_2 in the ambient, the carbon compound on the surface was removed by etching before cells were fabricated. The results of the baseline process are summarized in Table 25. The efficiency of the cells were lower than the previous lower grown ribbons. (See Table 1 and Table 3 in Annual Report (Phase III) (Reference 1)). Part of the reason was that these ribbons were 4 ohm-cm while the previous ones were 1 ohm-cm, the lower resistivity leading to higher Voc. Also, the present ribbons gave variable cell performance. Overall, the ribbons grown with CO_2 were only marginally better than the ribbon grown without CO_2. In some cases, the present ribbons had Isc and CFF comparable to the values obtained earlier. In other cases, parameters for the present ribbons were lower than those for previous ribbons. Considering these ribbons were grown as part of the experimentation and optimization process at higher growth rates, these variations are not suprising.

Minority Carrier Diffusion Length

Back up (Dark D.C.) L_D measurements were performed on selected cells. The results are listed in Table 26. The data didn't indicate a decisive advantage of the "CO_2 on" cells and the values were low in general with some exceptions. As indicated in the attached figure for the ribbon geometry, the properties of the ribbons varied across the width but were similar along the length of growth. This backs up the conclusions of the previous section which were based on Jsc data.

17-175 Series

To continue the study of fast growth (3.8cm/min.) EFG ribbons another batch of ribbon (the 17-175 series) was processed. For each 10x5cm ribbon, eight 2x2cm cells (instead of four-last time) were made to get better statistics. For part of the material grown with CO_2, the carbon compound on the ribbon surface was not removed to see if there was any difference. Baseline processing was applied and the results for the cells are summarized in Table 27. The cells from ribbons grown with CO_2 were better in Jsc and efficiency in a more pronounced fashion than the last experiment. However, there were shunting problems in these ribbons caused by inclusions or other reasons. Figure 19 shows the distribution of Jsc on EFG Ribbon 17-175-1E-52 and it is obvious that more variation occurs along the width (the 10cm side) than in the growth direction (the 5cm side), consistent with the results above. Etching off the carbon compound on the ribbon did not have a marked effect on the cell performance in this case. this was not the case in the past. An etching step was necessary for material reported in the 7th Quarterly Report. Nevertheless, a etching step is still recommended for cell processing, partly to ensure good cleanliness.

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE 25

SUMMARY OF SOLAR CELLS MADE FROM EFG 17-200 SERIES

		Voc (mV)	Jsc (mA/cm²)	FF (%)	(%)	REMARKS
17-200-1A (4 CELLS)	AVE. S.D. RANGE	495 ±10 480-504	22.5 ±1.5 20.2-23.6	71 ±4 65-73	7.9 ±.7 7.1-8.6	CO_2 OFF
17-200-1B (2 CELLS)	AVE. S.D. RANGE	515 ±7 510-520	23.0 ±1.2 22.1-23.8	76 ±1 75-77	9.0 ±.5 8.6-9.3	
17-200-1D (3 CELLS)	AVE. S.D. RANGE	529 ±5 524-534	24.2 ±.2 24.0-24.3	74 ±3 70-76	9.4 ±.4 9.0-9.7	
17-202-1C (4 CELLS)	AVE. S.D. RANGE	505 ±17 486-516	22.6 ±1.6 20.8-24.2	73 ±1 72-74	8.3 ±.9 7.4-9.2	CO_2 ON
17-203-1D (2 CELLS)	AVE. S.D. RANGE	499 ±1 498-500	21.0 ±.3 20.8-21.2	73 ±1 72-74	7.7 ±.3 7.5-7.9	
17-203-1E (2 CELLS)	AVE. S.D. RANGE	487 ±7 482-492	19.8 ±1.4 18.8-20.8	71 ±4 68-74	6.9 ±.2 6.7-7.0	
ACCUMULATIVE AVE OF "CO_2 ON" CELLS (13 CELLS)		508	22.4	73	8.4	

CZ CONTROL (4 CELLS)	AVE. S.D. RANGE	583 ±2 580-584	27.9 ±.4 27.4-28.3	78 ±1 77-78	12.6 ±.2 12.3-12.9

Table 26

MINORITY DIFFUSION LENGTH OF EFG 17-200 SERIES

	CELL #	L_D (μm)	REMARKS
17-200-1A	3 4 7 8	37 39 49 87	CO_2 Off
17-200-1B	5	28	
17-200-1D	2	43	
17-202-1C	1 2 5 6	83 83 29 29	CO_2 on ohm equivalent
17-203-1D	6	25	
17-203-1E	1	18	
CZ Control	3	183	

LOCATION OF THE CELLS ON THE RIBBON

1	3	5	7
2	4	6	8

GROWTH DIRECTION

TABLE 27

ORIGINAL PAGE IS
OF POOR QUALITY

SUMMARY OF SOLAR CELLS MADE FROM 17-175 SERIES

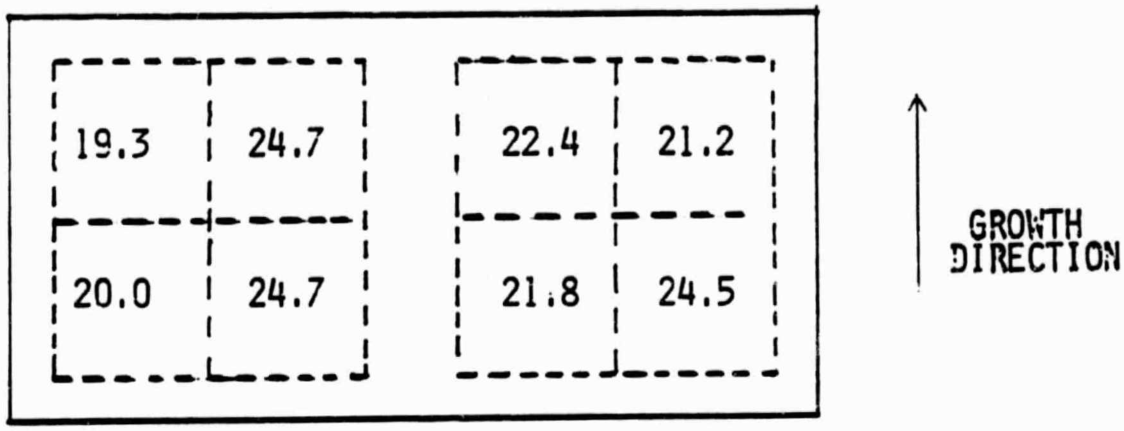
		VOC (mV)	Jsc (mA/cm)	CFF (%)	(%)	REMARKS
	AVE	519	21.2	72	7.9	
17-175-1A-2	S.D.	±8	±1.15	5	±.8	
(7 CELLS)	RANGE	504-530	19.8-22.8	62-75	6.4-9.0	
	AVE	493	20.1	61	6.2	
17-175-1A-6	S.D.	±34	±1.2	±16	±2.1	CO_2 OFF
(5 CELLS)	RANGE	434-518	19.4-21.8	61-74	2.7-8.3	
ACCUMULATIVE AVERAGE OF "CO_2 OFF" CELLS (12 CELLS)		508	20.7	67	7.2	
	AVE	539	22.3	73	8.9	
17-175-1E-52	S.D.	±12	±2.1	±3	±1.1	
(8 CELLS)	RANGE	516-554	19.3-24.7	68-77	7.0-10.4	
	AVE	505	21.3	59	6.4	
17-175-1E-56	S.D.	+40.4	+2.4	+15	+2.2	CO_2 ON
(6 CELLS)	RANGE	432-546	17.6-22.6	35-70	3.4-3.1	
ACCUMULATIVE AVERAGE OF "CO_2 ON" CELLS (14 CELLS)		524	21.9	67	7.8	

	AVE	585	28.2	75	12.4
CZ CONTROL	S.D.	±2	±.6	±3	±.4
(4 CELLS)	RANGE	582-586	27.5-28.9	71-78	12.0-12.7

FIGURE 19

ORIGINAL PAGE IS
OF POOR QUALITY

DISTRIBUTION OF Jsc ON
EFG RIBBON 17-175-1E-52



F. Small Diode Grain Boundary Study

1.0 Small Diode Fabrication

As the goal of DOE for the FSA project is shifting towards fundamental understanding rather than technology development and the number of new silicon sheets available for study is getting lower, a more consistent technique was developed in making small mesa diodes. These would allow us to make more detailed study of junction characteristics and localized properties such as grain boundary, etc. on existing materials.

Previously, mesa diodes were etched out by protecting certain area of an existing solar cell with circular dots of black wax and using the existing grid line as metal contacts. The drawback of such a procedure is that the coverage of diodes were limited by the location of the grid lines and the existing metal mask we have for circular wax dots do not necessarily match the various grid lines locations well. Therefore, the resultant number of usable diodes is sometimes low, especially if local properties such as grain boundaries are of interest. In order to have greater coverage and more consistent metal contacts, a two piece set of existing diode masks was used. This provides a close-packed array of rectangular diodes of the size of 0.125 x 0.25cm^2 with corresponding rectangular metal pads of 0.072 x 0.077cm^2 in the middle for metal contact. After formation of the junction and HF cleaning to remove diffusion glass, the following process procedures were followed:

1) Application of photoresist masking technique using the metallization mask.
2) Evaporation of Ti-Pd-Ag (2um Ag) and lift-off.
3) Application of 7500A of CVD SiO_2.
4) Application of photoresist masking technique using the diode mask.
5) Etch unprotected CVD SiO_2 with HF.

6) Etch mesas with a mild 2HF; 15 HNO_3; 5 acetic acid solution for 30 sec. This is a critical step. 30 sec. of 2-15-5 solution is enough to etch away the 0.3um junction to form isolated mesas but the fraction of HF is low enough such that part of the 7500A SiO_2 still remains after 30 sec. to protect the diodes, eventhough the photoresist might be gone. What remains to be done is to remove the remaining photoresist and CVD SiO_2 and apply back contact.

2.0 Grain Boundary Study On UCP Material

Selected wafers of UCP were used in making small diodes as described in the previous paragraph. The diodes were identified as either grain boundary diodes or single crystal diodes. The grain boundary diodes usually included points where two or more grain boundaries intersected. Dark current measurements were made on the diodes. A typical set of results is shown in Figures 20A through 20C. Figure 20A shows dark currents of grain boundary diodes from a wafer cut from the top of UCP ingot C4-21A while Figure 20B shows dark currents of single crystal diodes from the same wafer. One can see the position of the I-V curves for the grain boundary diodes are slightly to the left of the single crystal ones with some overlapping. This implied that the grain boundary diodes would have shorter characteristic lifetimes in general and would have lower Voc if tested as solar cells. Similar results were observed in diodes made on a randomly chosen wafer. However, diodes from a wafer at the bottom of UCP Ingot C4-21A do not show any difference between the two kinds and (single crystal, grain boundary) and tended to have characteristics equivalent to the grain boundary diodes of the other wafers. This seems to indicate that other problems, possibly impurity related, also exist in this wafer. This consistent with gettering results reported in Section D-2. Figure 20C shows the dark current of a CZ-Silicon

control diode. The I-V curves are to the right of all the other curves and indicate better lifetimes and diode qualities.

Minority Carrier Diffusion Length

Representative diodes of the grain boundary type and the single crystal type were selected for minority carrier diffusion length measurements. The results of individual diodes are listed in Table 28. From the twelve measurements (six of each type) being made, one can see that in general the single crystal diodes have a higher minority carrier diffusion length, with two exceptions. In general, the L_D values for UCP silicon of either kind were lower than that of CZ-silicon. Also, in the randomly chosen samples, there seems to be other factors involved as well as grain boundary in determining the diffusion lengths.

ORIGINAL PAGE IS
OF POOR QUALITY

FIGURE 20A

DARK IV OF A GROUP OF GRAIN BOUNDARY DIODES
ON A WAFER ON THE TOP OF INGOT C4-21A

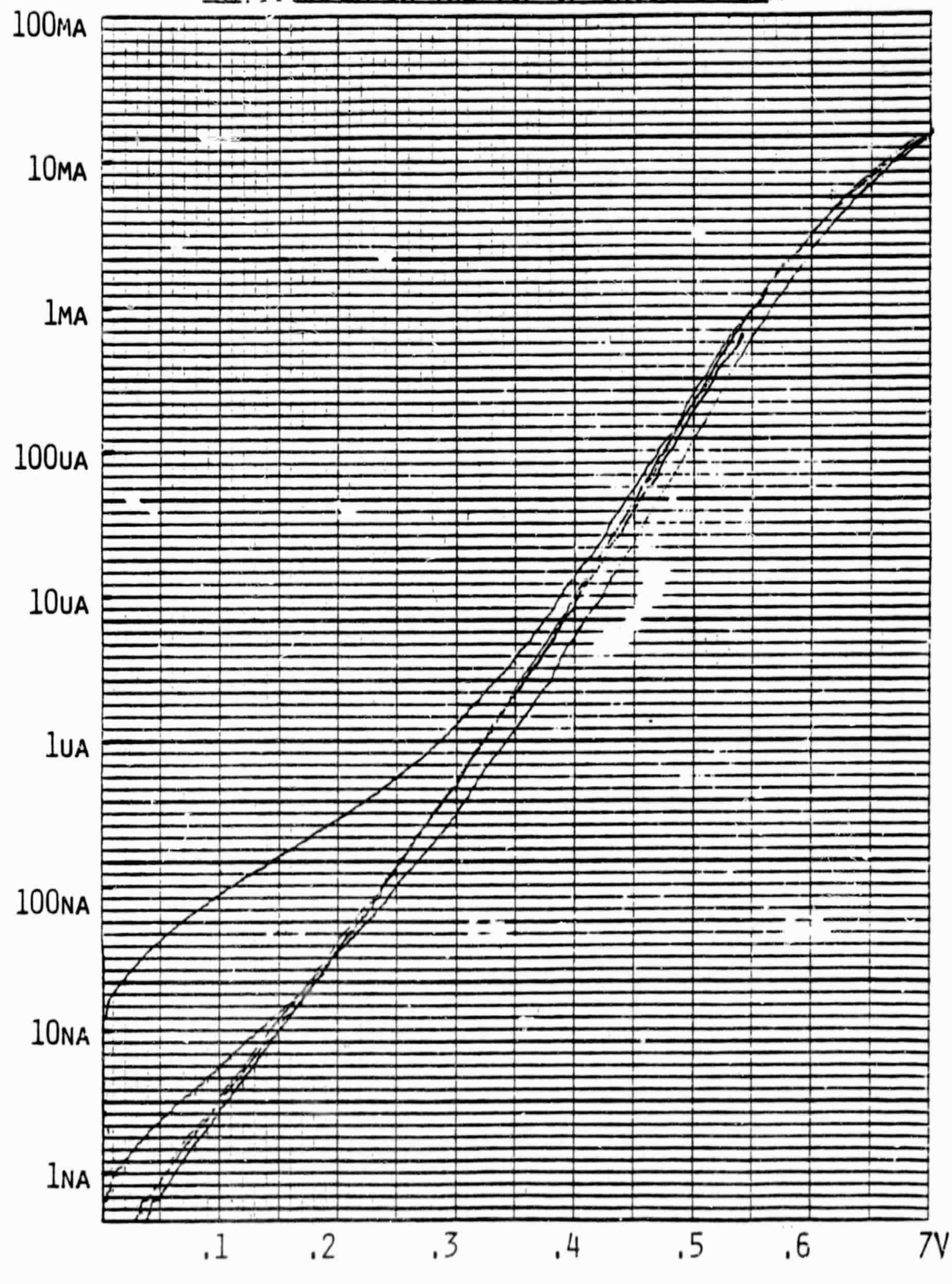
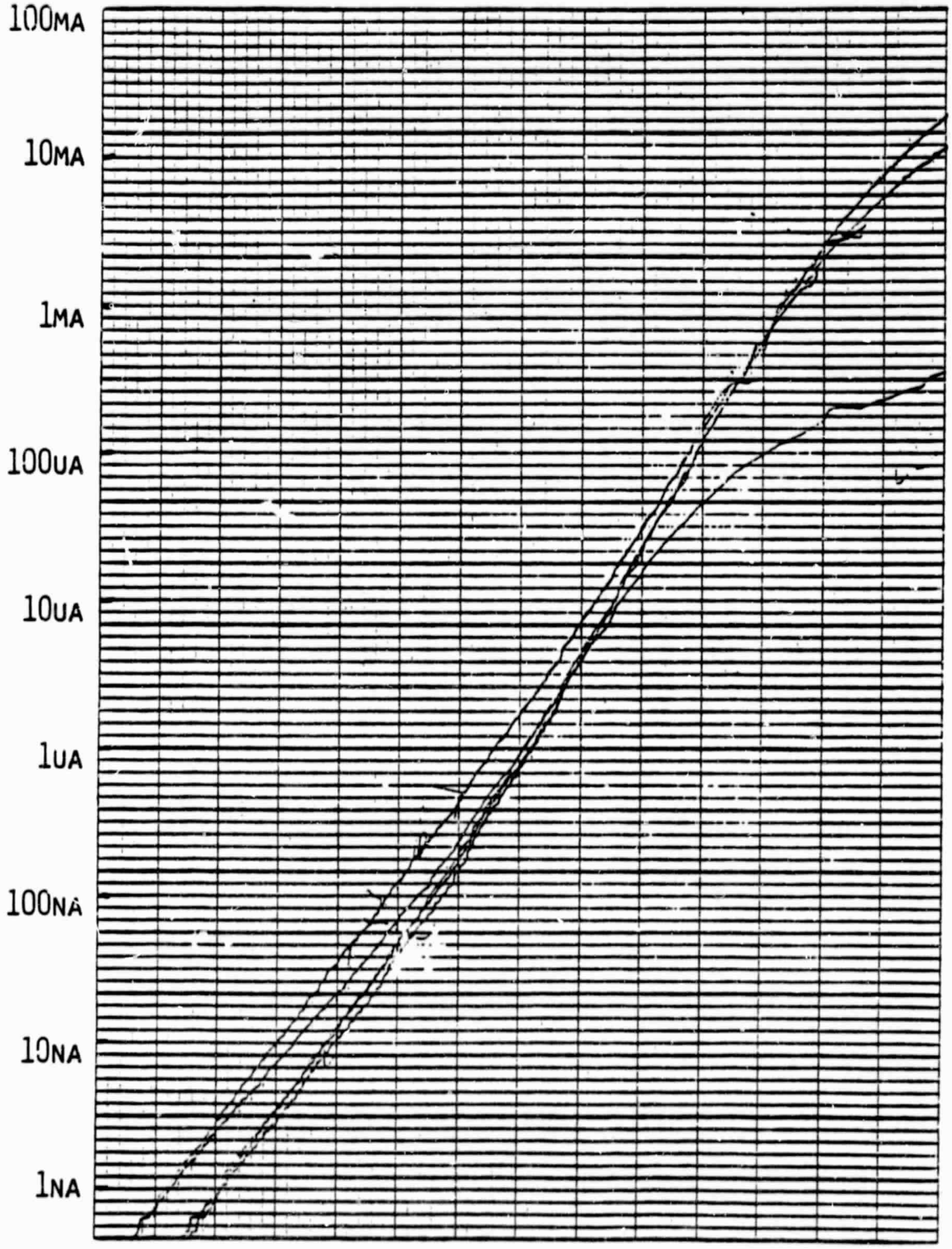


FIGURE 20B

DARK IV OF A GROUP OF SINGLE CRYSTAL DIODES ON A WAFER ON THE TOP OF INGOT C4-21A

ORIGINAL PAGE IS OF POOR QUALITY



ORIGINAL PAGE IS
OF POOR QUALITY

FIGURE 20C

DARK IV OF A GROUP OF CZ CONTROL DIODES

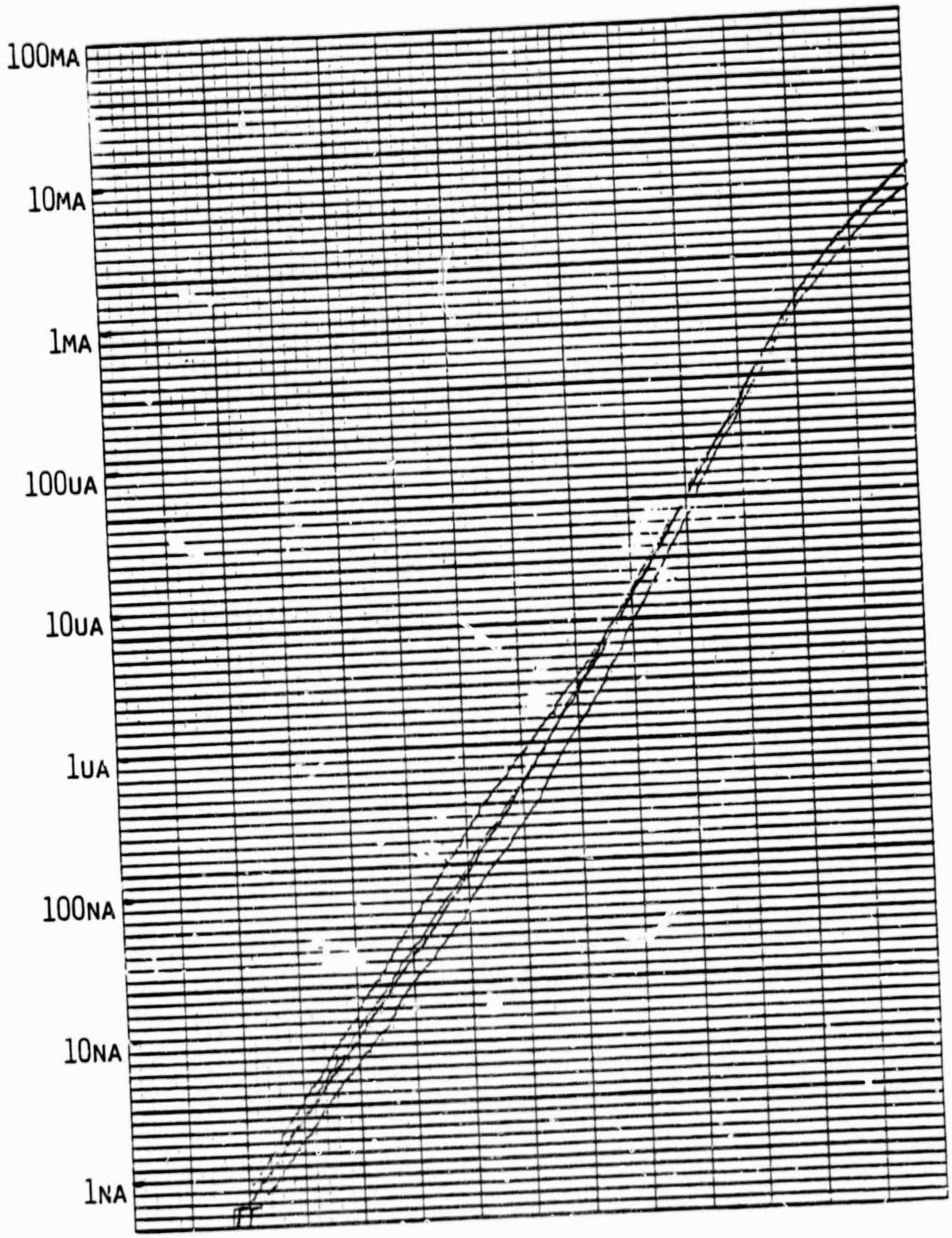


TABLE 28

MINORITY CARRIER DIFFUSION LENGTHS OF DIODES

MADE FROM UCP SILICON

WAFER	DIODE #	L_D (um)	CHARACTER
A	1	133	Single Crystal
	2	152	Single Crystal
(Top Of	3	42	Grain Boundary
C4-21A)	4	46	Grain Boundary
B	1	66	Single Crystal
	2	25	Single Crystal
(Bottom Of	3	21	Grain Boundary
C4-21A)	4	27	Grain Boundary
C	1	68	Single Crystal
	2	119	Single Crystal
(Random	3	40	Grain Boundary
Source)	4	112	Grain Boundary
Cz Control	1	190	Single Crystal

III. CONCLUSIONS

UCP Silicon

- Light gettering did not improve on the cells from randomly selected wafers (i.e. they are not from any specific ingot). High efficiency processes such as SJ and MLAR improved cells efficiency, but the Al paste BSF did introduce shunting problems; therefore evaporated Al BSF was prepared and efficiency up to 14% was achieved (compared to CZ control 15%).
- $10x10cm^2$ baseline cells were fabricated using a extended four inch cell mask and photoresist. The resultant average effic ency of 10.8% was consistent with $2x2cm^2$ baseline results.
- Ingot 5848-13C had shunting problems on the top layers and low Jsc in the middle layers. Also the middle layers response strongly to severe gettering. These indicated impurity problems in this ingot.
- In the more severely gettered samples of the above ingot, a reverse light biased effect occured in diffusion length measurement i.e., the light bias reduced L_D. But a positive light biased effect was observed in lightly gettered or non-gettered samples.
- Ingot C-4-21A did not have the problem of ingot 5848-13C and demonstrated results close to the randomly selected wafers. The top half of the ingot is slightly superior to the bottom half as demonstrated in the Jsc and L_D results. Slight gettering did help to equalize in the Jsc and narrow the gap in L_D.

Comparison of UCP, New Silso and HEM

- Similar baseline results for typical samples of all three materials except somewhat higher efficiency for the single crystal portion of HEM and lower for the fine grain portion of Silso.

- o After severe gettering, only slight improvements were observed in Silso and UCP (ingot 5848-13C was not used) and no change for HEM.
- o All three materials respond to higher efficiency processes such as SJ and MLAR. HEM had shunting problems with evaporated Al while Silso, and UCP had no problem. The highest values in this run was 13.9% for UCP, 13.6 for Silso and 14.4 for HEM with highest CZ control 15.7%. Again the difference in performance of these three materials was not pronounced.

EFG Ribbon

- o Baseline results of two series of new fast grown EFG ribbon were lower than those of earlier slower grown ones. Also the advantage of CO_2 treated ribbon was not as pronounced.
- o Jsc and L_D results indicated variation along the width of the ribbon, but relative uniformity along the direction of growth.

Small Diode Study

- o Small mesa diodes were fabricated on UCP material and the feasibility of this technique in studying the influence of the grain boundaries was demonstrated.
- o Single crystal diodes of UCP are in general more superior than diodes containing grain boundary, but the grain boundaries are not the only factor limiting performance.

Finally, since this project is now entering a new phase, it is appropriate to summarize the results in the last four phases. Figure 21 shows the relation between AM1 efficiency and minority carrier diffusion lengths for a wide variety of sheet materials. Present phase results are presented along with

the curves equivalent to those presented in the Phase II Annual Report. Please refer to it for earlier materials. Also L_D in the earlier reports are smaller than the present one due to a more accurate way of calculation in the present report. In the present curves, most of the materials used in "advanced processing" did not have strong BSF effect for most materials after Phase II were of lower resistivity. The results of this work support the fact that diffusion length is the most dominant parameter in determining cell efficiency

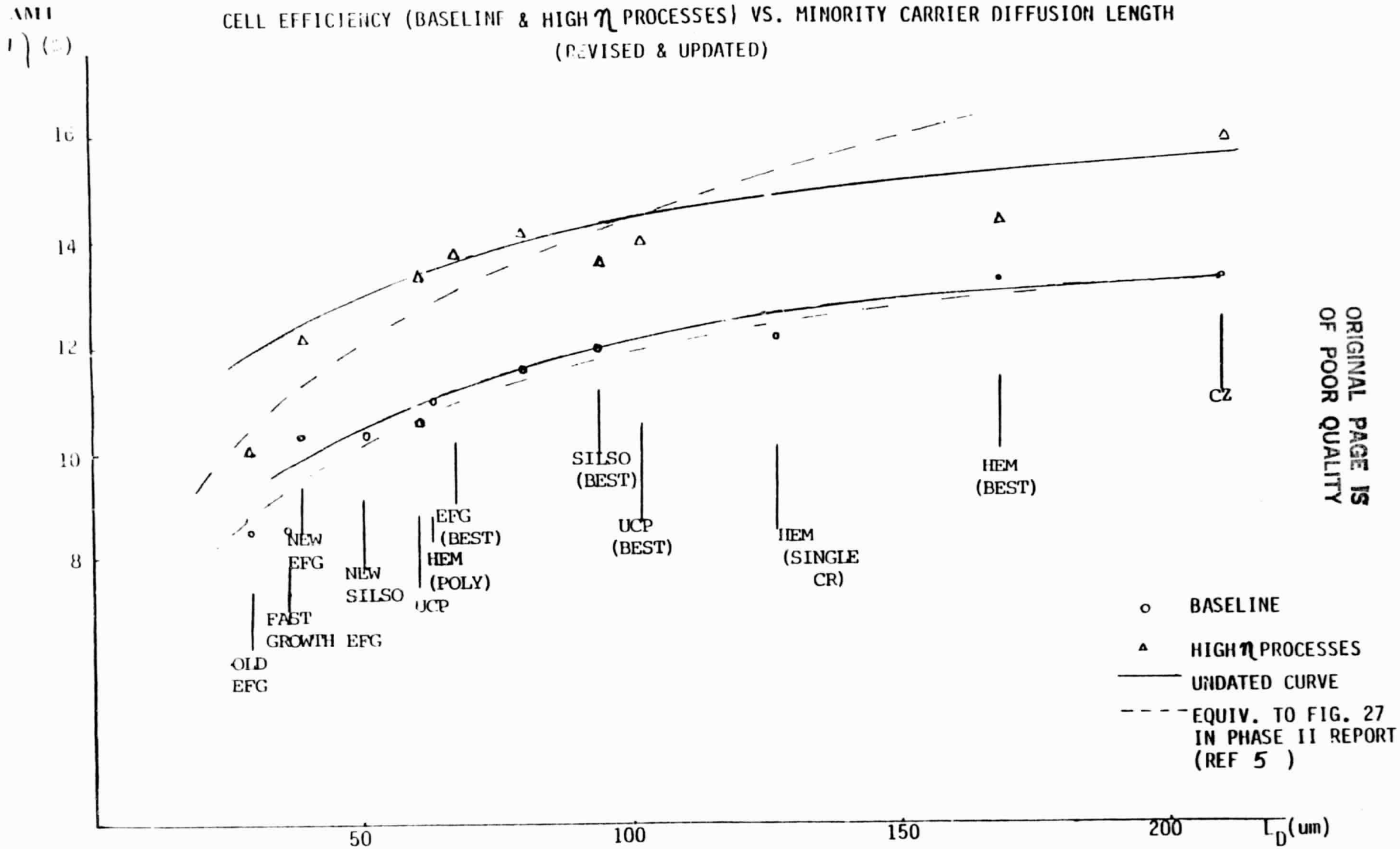
Many physical properties such as grain size, dislocation densities etc. can affect the minority carrier diffusion lengths. Other factors such as SiC inclusions in some of the cast materials and non-flat surfaces in some ribbons can cause poor diode characteristics or shunting and hence low Voc and CFF. Non-flat surfaces can also cause fabrication problems in handling and cutting etc. Material such as SOC had problems in making back contact because of the kind of substrate used.

We believe that overall the approach that has been used throughout the four phases of the program has been shown to be useful and it has successfully provided a fair and direct basis of evaluating the various sheet materials. It is good to see that many of these materials have matured into commercialization, and we hope that some guidance in this evolution was provided by the evaluation work.

FIGURE 21

CELL EFFICIENCY (BASELINE & HIGH η PROCESSES) VS. MINORITY CARRIER DIFFUSION LENGTH

(REVISED & UPDATED)



ONLY PHASE III AND IV DATA POINTS ARE DISPLAYED

IV. WORK PLAN STATUS

Phase V will extend the small diode technique to other materials such as HEM and Silso. Other techniques such as small light spot scan will also be applied and extended to study limiting factors of various sheet materials in cooperation with JPL. Cell fabrication will also be performed when new materials become available or in support of new material treatments such as new surface or grain boundary passivation techniques if they become available.

V. REFERENCES

1. H.I. Yoo et al, "Silicon Solar Cell Process Development, Fabrication and Analysis". JPL Contract No. 955089, Annual Report (Phase III) June 1981.

2. H.I. Yoo et al, "Silicon Solar Cell Process Development, Fabrication, and Analysis". JPL Contract No. 955089 Annual Report (Phase I), June 1979.

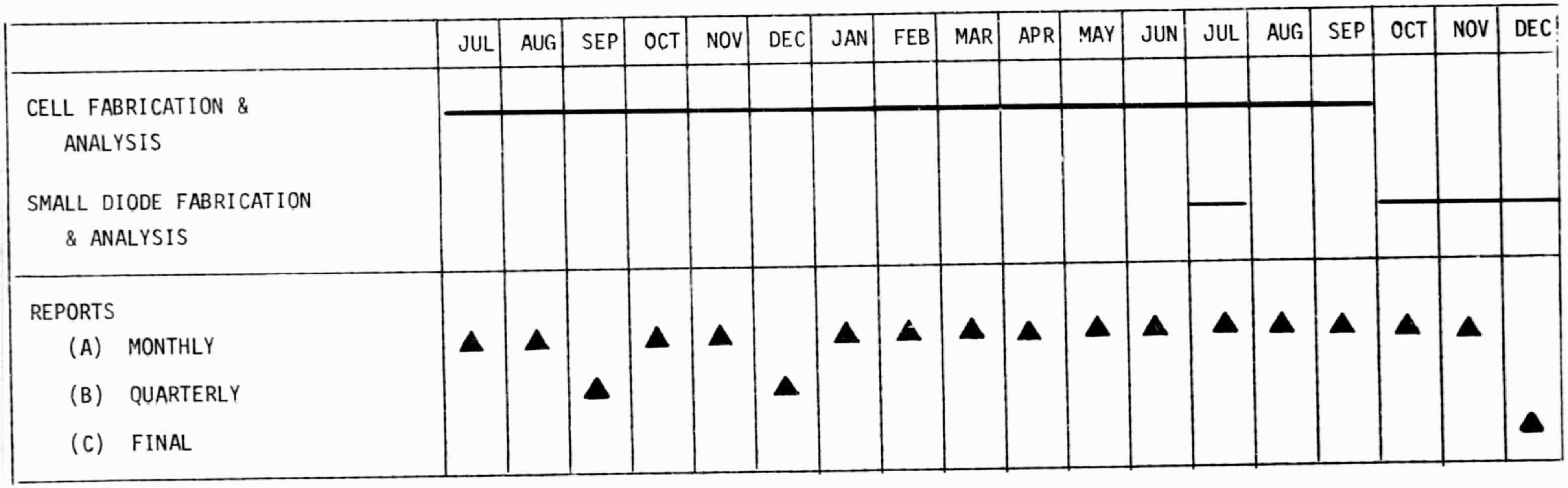
3. J.S. Culik and S. Katz "Method To Monitor The Quality of Screen-Printed Aluminum Paste Back Surface Field". Proceedings of 15th IEEE Photovoltaic Specialists Conference, p.512-517, 1981.

4. L. J. Cheng et al, "Mechanisms of Photon-Induced Changes in Silicon Solar Cell Parameters". Proceedings of 13th IEEE Photovoltaic Specialists Conference, p.1337, 1978.

5. H.I. Yoo et al, "Silicon Solar Cell Process Development, Fabrication and Analysis", JPL Contract No. 955089 Annual Report (Phase II), June 1980.

APPENDIX I

TIME SCHEDULE


JUL
AUG
SEP
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
CELL FABRICATION & ANALYSIS
SMALL DIODE FABRICATION & ANALYSIS
REPORTS
(A) MONTHLY
(B) QUARTERLY
(C) FINAL

APPENDIX II

ABBREVIATIONS

V_{OC}: Open Circuit Voltage

I_{SC}: Short Circuit Current

J_{SC}: Short Circuit Current Density

I_{SCR}: Short Circuit Current (Red Response) at Wavelength Above $\sim$.6um

I_{SCB}: Short Circuit Current (Blue Response) at Wavelength Below $\sim$.6um

CFF: Curve Fill Factor

η : Solar Cell Conversion Efficiency

L: Minority Carrier Diffusion Length (D.L.)

I_{MAX}: Current at Maximum Power Point

V_{MAX}: Voltage at Maximum Power Point

BSF: Back Surface Field

BSR: Back Surface Reflector

V_B: Bias Voltage

I_o: Diode Saturation Current

HEM: Heat Exchanger Method

EFG: Edge Defined Film-Fed Growth

SOC: Silicon on Ceramic

RTR: Ribbon-to-Ribbon

UCP: Ubiquiton Crystallization Process

SPV: Surface Photovoltage

MLAR: Multi Layer Anti-Reflective

R_s: Series Resistance